Adding it Up

A global assessment of plastic additives leakage

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Earth Action has taken due care in the preparation of this report to ensure that all facts and analyses presented are as accurate as possible within the scope of the project. However, the accuracy of the presented information is not guaranteed and Earth Action is not responsible for decisions or actions taken on the basis of the content of this report.

Note for the reader: This report serves as an appeal for additional data on additives in plastics. If you possess more precise information regarding additive content in plastics categorised by polymer, application, sector, or release rates, we encourage you to reach out to the corresponding author.

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About us

EA - Earth Action is a mission-driven research consultancy and member of the European Network of Ecodesign Centres (ENEC). In addition to supporting organisations through a broad service offering, EA regularly works to identify and address critical sustainability knowledge gaps, developing the data and applying insights to create research trusted by scientists and actionable by all.

EA is particularly recognized for expertise and leadership in the field of plastic pollution, contributing novel research, perspectives, frameworks, and methodologies to help global organisations address the issue within their own realm and beyond.

Since 2017 EA has published 12 peer-reviewed reports on plastic pollution topics www.e-a.earth/publications. An early report "Primary Microplastics in the Ocean" published in 2017 by IUCN, was one of the first studies to shed light on the impact of primary microplastic on the environment (mainly from tyres and textiles).

In 2022, EA presented another novel report on microplastics with the "Plastic Paints the Environment" report, highlighting the significant contribution of paint to microplastic leakage in the environment.

EA co-developed the first plastic footprint methodology in 2020 (The Marine Plastic Footprint, IUCN 2020) and (The Plastic Leak Project, 2020), which has enabled companies worldwide to assess the impact of plastic used in their products, services, and operations. Since 2020 governments have also been supported in their efforts to address plastic pollution by the EA-led National Guidance for Plastic Pollution and Shaping Action (2020), released in partnership with UNEP and IUCN.

More recently EA has convened the Plastic Footprint Network https://www.plasticfootprint.earth/, a broad stakeholder initiative working to harmonise the methodologies and frameworks for assessing, measuring, and mitigating plastic pollution globally.

Another important EA contribution to addressing plastic pollution is PLASTEAX (www.plasteax.org), which was launched in 2021. PLASTEAX provides companies, NGOs, governments and other pollution stakeholders with polymer-specific waste management and leakage data for countries around the world. The valuable data within PLASTEAX regularly informs other plastic pollution research, including this study, and decision-making.

The EA team recognizes there is no single solution to plastic pollution and is committed to identifying and providing the data, ideas, insights, services, solutions and opportunities required for all stakeholders in the world of plastics to protect human health and global ecosystems from the ill-effects of plastic pollution.

Foreword

This comprehensive investigation into plastic additives represents a timely and vital undertaking in a field challenged by scarce data. Despite this scarcity, the report provides a compelling initial glimpse into the expansive landscape. As supporters, the Plastic Soup Foundation, the Plastic Health Council and A Plastic Planet endorse this collaborative effort, emphasizing the pressing need to comprehend the intricate nature of plastic materials and advocate for a cleaner chemistry.

Rather than focusing solely on a few additives, this report delves into a complex ecosystem encompassing thousands of potential combinations and over 10,000 additives utilized in plastic formulations. Within this vast diversity lies the impetus for a more nuanced understanding.

The secrecy surrounding the chemical composition of plastics poses a significant threat to human health and the environment. This lack of transparency not only endangers our well-being but also hampers our ability to address the plastic crisis effectively. A comprehensive grasp of the chemical intricacies is essential to manage and recycle plastics without unintended harm.

Hence, this report arrives at a pivotal moment, urging a holistic approach to combatting chemical pollution stemming from plastics. It serves as a call for recalibrating plastic production chemistry and demanding increased transparency.

The insights and recommendations in this report aim to inspire stakeholders, policymakers, industry leaders, and the public to adopt a broader perspective. Through a commitment to improved chemistry practices and a focus on transparency, we can pave the way for a safer, more sustainable future.

May this report serve as a catalyst for change, igniting a collective shift towards a more responsible, informed, and conscientious approach to the use and management of plastics.

Maria Westerbos, Founder, Plastic Soup Foundation:

"The results of EA Earth Action's *Adding it up* report are a sobering reminder of how additives toxify both our planet and our bodies. We should never forget that all these chemicals are added to plastics and in that way are released in the entire ecosystem, including our own bodies. We now must see action."

"It is imperative that coordinated international cooperation between both the private sector and policymakers addresses additive leakage to preserve human health for the next generation."

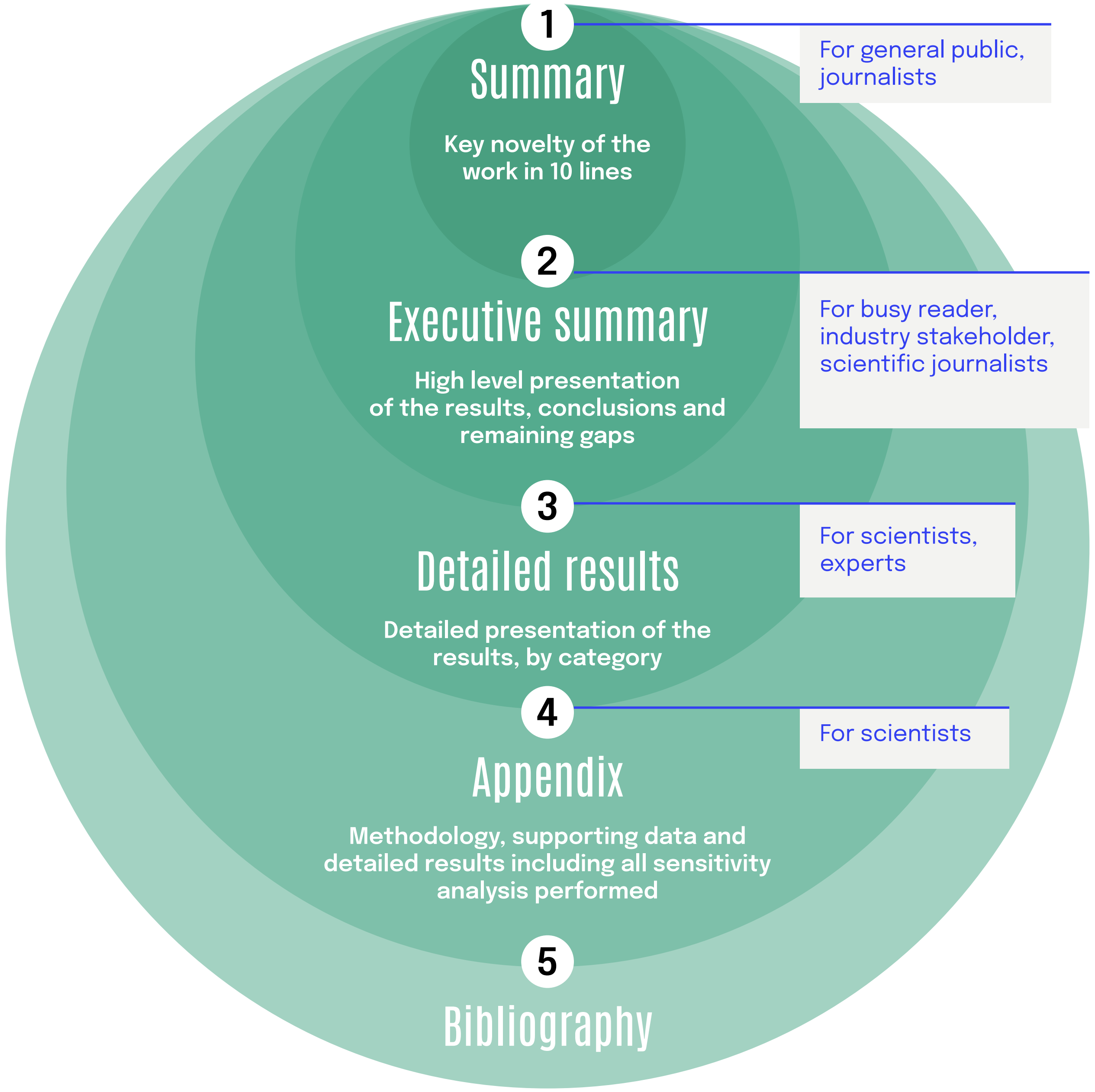
Sian Sutherland, CoFounder of A Plastic Planet and Plastic Health Council:

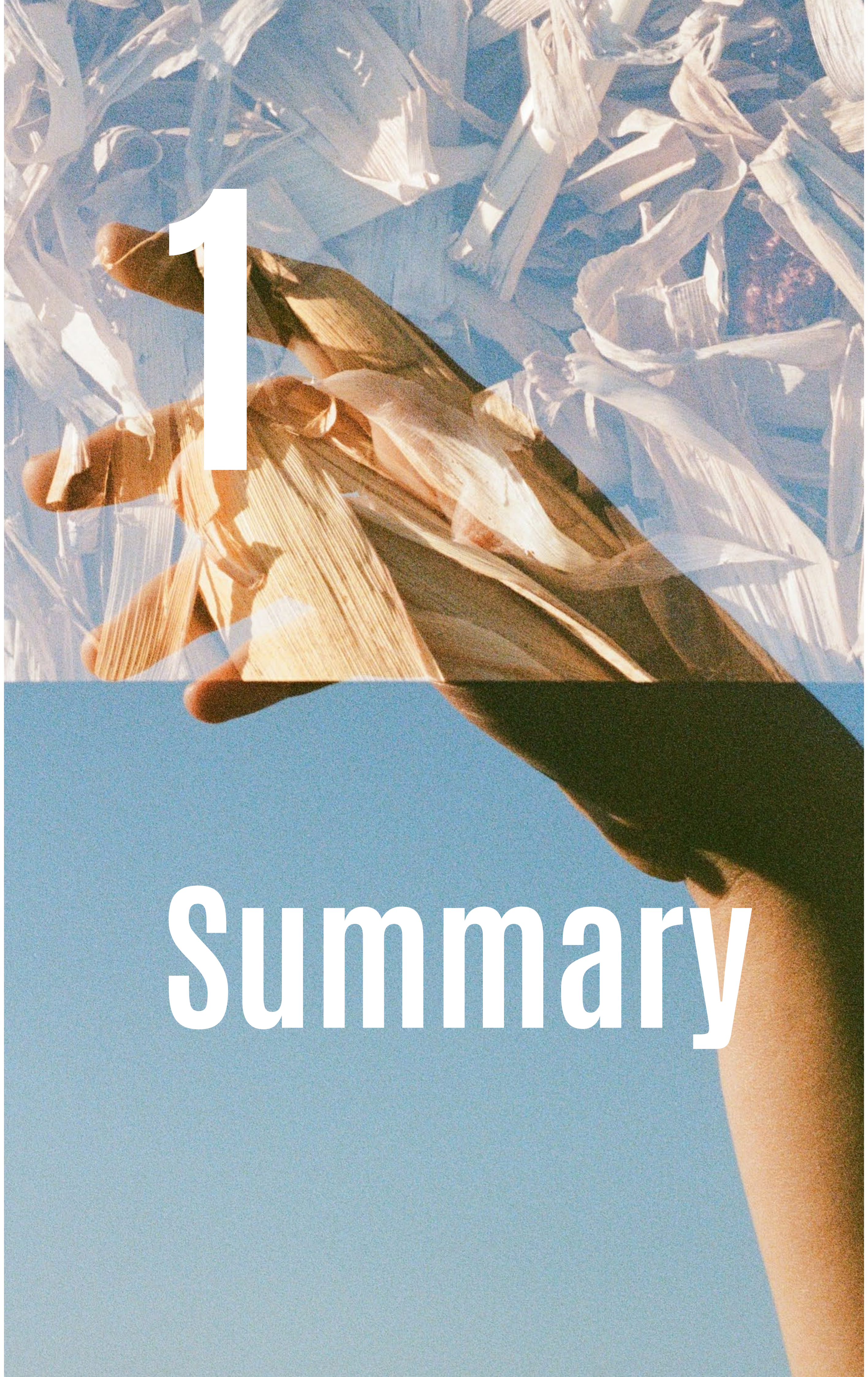
"The omnipresence of plastic in our lives today belies its danger. Plastic is not on the periodic table, like cobalt or copper. It is a mixture of chemicals, many of them toxic to human health. In only a few decades we have infected every inch of our planet with such chemicals, leaching into our environment at escalating levels. The danger to next generations is clear and strong policy is urgently needed. But for policy to change, we need clarity on the extent of the crisis. This EA report exposes current practice and calls for safer chemistry. It is possible. But only if we demand it."

Lists of abbreviations

6PPD	N-phenyl-N´-(1,3-dimethylbutyl)-p-phenylenediamine
6PPDq	N-phenyl-N'-(1,3-dimethylbutyl)-p-phenylenediamine quinone
ATBC	Acetyltributylcitrate
BFRs	Brominated flame retardants
BTZ	Benzothiazole
CO_2	Carbon dioxide
CPPdb	Database of Chemicals associated with Plastic Packaging
DEHA	Diethyl adipate
DEHP	Di-2-ethylhexyl phthalate
DEP	Diethyl phthalate
DnBP	(n-butyl) phthalate
EDC	Endocrine disrupting chemicals
FDA	Food and Drugs Administration
HDPE	High-density polyethylene
HOCS	Hydrophobic organic chemicals
INC	Intergovernmental Negotiating Committee
IUCN	International Union for Conservation of Nature
kt	Kilotonnes (metric tonnes)
MCCs	Medium-Chain Chlorinated Paraffins
MEHP	Mono-(2-ethylhexyl) phthalate
Mt	Million tonnes (metric tonnes)
MTBE	Methyl tert-butyl ether
MWI	Mismanaged waste index
NIAS	Non intentionally added substances
NICU	Neonatal Intensive Care Unit
PBA	Bisphenol A
PBDEs	Polybrominated diphenyl ethers
PBT	Persistent Bioaccumulative Toxic
PCBs	Polychlorinated biphenyls
PCDD	Polychlorinated dibenzodioxins
PE	Polyethylene
PET	Polyethylene terephthalate
PHAs	Polyhydroxyalkanoates
PLP	Plastic Leak Project
POPs	Persistent Organic Pollutants
PP	Polypropylene
ppb	Parts per billion
ppm	Parts per million
PS	Polystyrene
PVC	Polyvinyl chloride
SCCPs	Short-chain chlorinated
TRWP	Tyre and road wear particles
UNEP	United Nations Environment Programme
UV	Ultra Violet
VOCs	Volatile organic compounds
vPvB	Very Persistent and very Bioaccumulative

The EA report structure





1 Summary

Plastic additives contribute significantly to ocean and terrestrial pollution

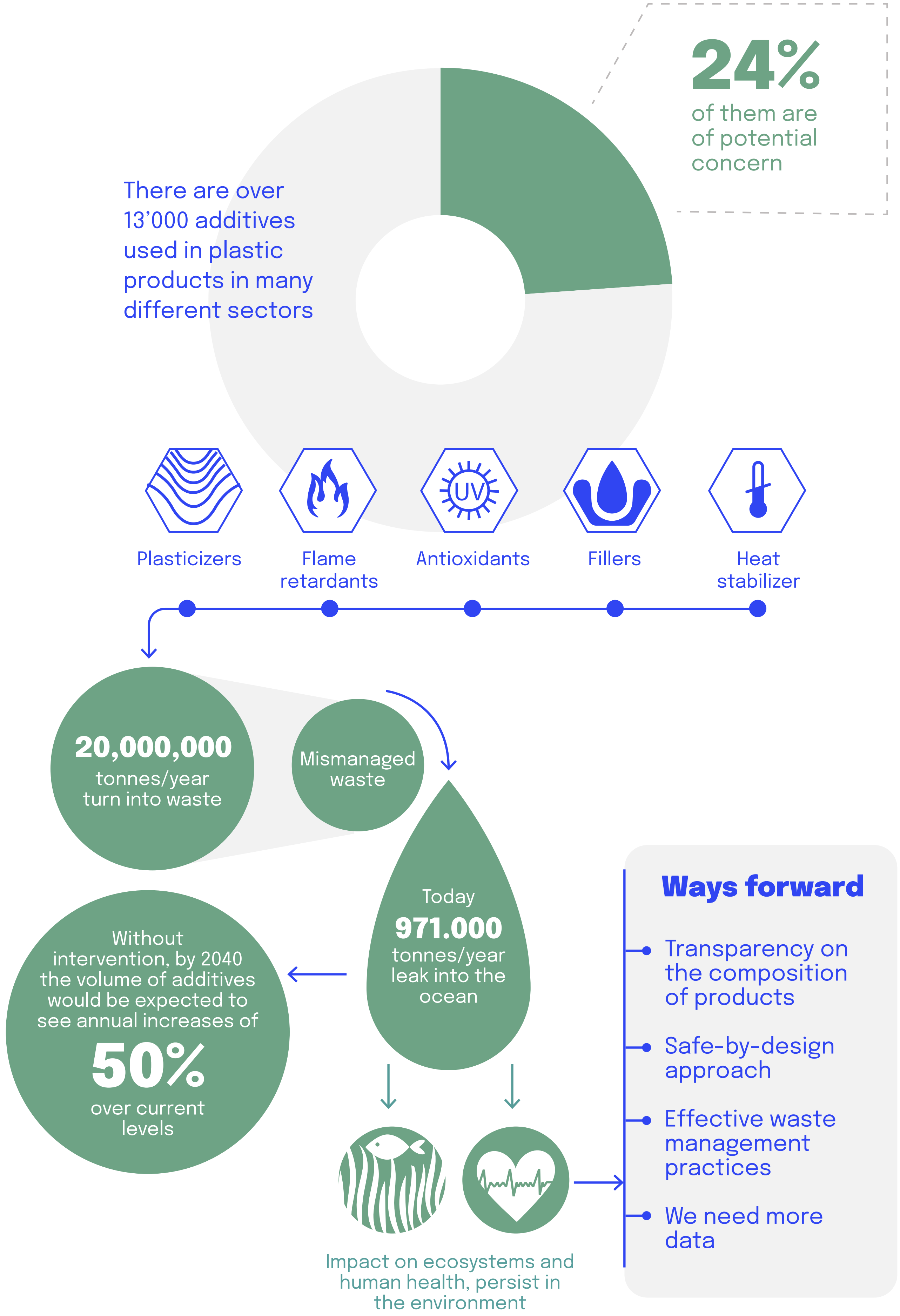
This study reveals that additives contribute nearly 1 million tons of pollutants to ocean leakage annually, approximately 10% of overall polymer leakage. This finding underscores the urgent need to include additives in thorough assessments of plastic pollution.

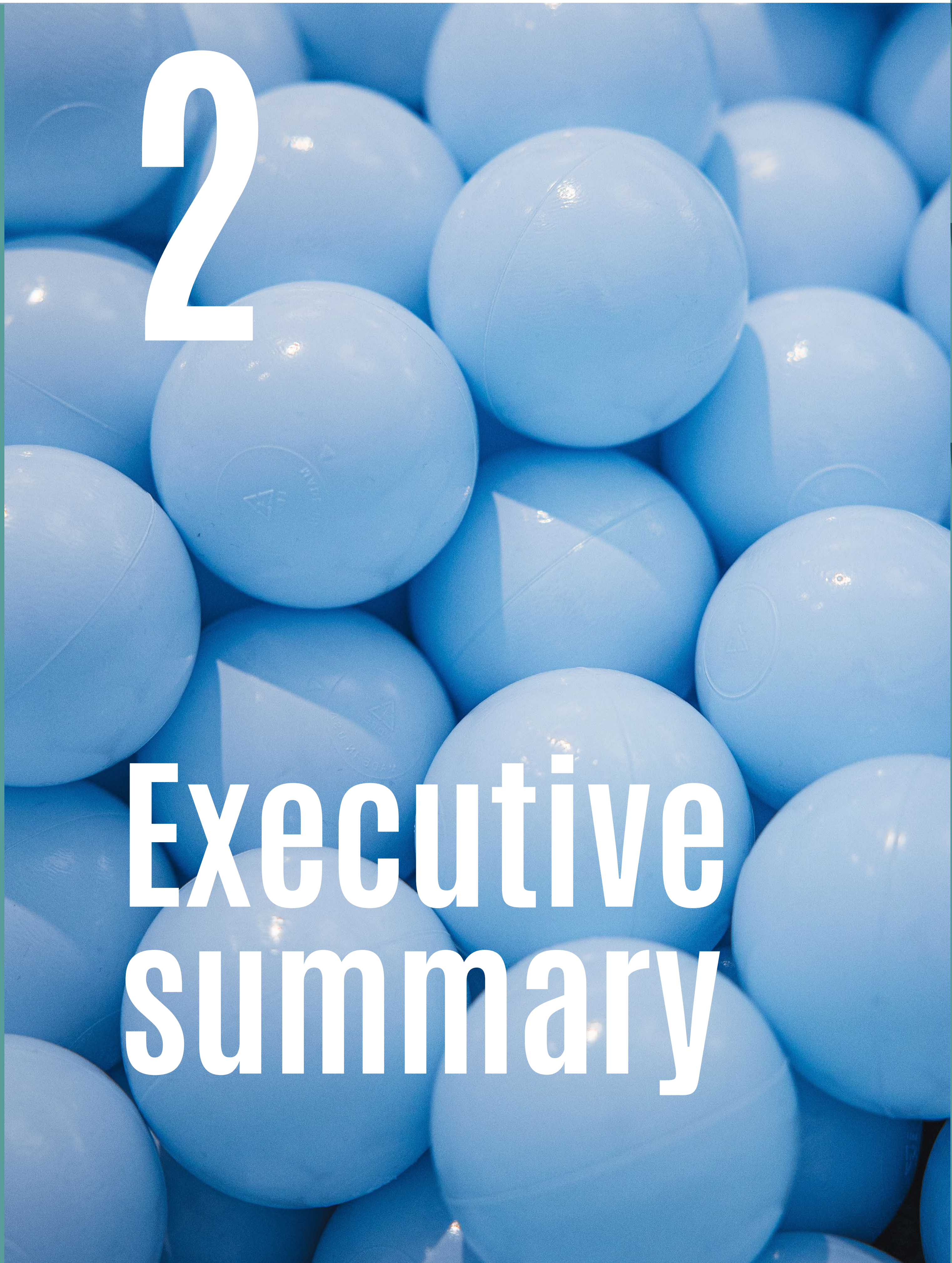
Uncertainties and lack of transparency are still important obstacles to studies of additives

Assessing the impact of additives remains a formidable challenge due to the inherent complexities and uncertainties surrounding these chemicals. The scarcity of transparent data and information on additives and fate of plastic products in many sectors compounds this difficulty. This study sheds light on the critical gaps in the understanding of the issue, emphasising the pressing need for increased transparency and data accessibility.

Plastic additives potentially have greater environmental and health impacts than the plastic itself

This report indicates that the environmental impact of additives might actually be of higher concern than the impact of the plastic polymers themselves, due to the low inertness and high reactivity of most additive formulations. Additives have been confirmed to have a detrimental effect on ecosystem health and human well-being. Further research into these chemical compounds is critical to addressing the threats emerging from the whole spectrum of plastic pollution.





2 Executive summary

2.1 Purpose of the Work and Research Questions

Amidst an expanded focus on the presence of chemicals in plastic, and specifically the inclusion of this issue on the Plastic Treaty negotiators' agenda, several noteworthy reports have recently been published.[(1)(2)] These reports consistently demonstrate that:

Beyond just polymers (the main component of plastic), many other substances are also present in plastic products.

The census on the number of additives in plastic is reaching over 13'000 different molecules, with this number rapidly growing.

These chemicals can be added intentionally or non-intentionally (NIAS) as a result of contamination, migration or degradation during or after the production process.

A significant number of the molecules found in plastic additives have not been studied and are not adequately regulated. These chemicals could cause health issues either through direct contact or via environmental pollution (e.g. when plastic waste is mismanaged or via microplastic leakage).

This study focuses on estimating the quantity of plastic additives leakage in the ocean and land, to shed light on one aspect of the broader plastic pollution problem. To achieve this, a comprehensive mathematical model has been employed to assess the quantities of plastic waste and additives in plastic products, and the corresponding expectation for amounts leaked into nature.

This work establishes a novel quantification of additives leakage due to waste mismanagement. To progress toward a better assessment of the full environmental and health impacts of plastic, and to offer a fresh and distinct perspective on the topic, the following research questions were considered in this study's design and execution:

1 What is the total quantity of plastic additives leaking into the ocean and land due to mismanaged plastic items? How is this expected to evolve in the future?

2 What is the approach used in the study and what knowledge and data gaps remain for further research?

3 How do specific sectors contribute to the leakage of additives into the ocean and land?

4 What are the health and environmental impacts of plastic additives?

5 What can be done to improve the overall situation?

2.2 Introduction

What are additives?

Additives are substances incorporated into plastic during production to enhance specific characteristics, improve performance, or facilitate processing. Among other features, additives are employed by manufacturers to alter plastic's appearance, durability, flame resistance, and/or flexibility. Each class of additives enables the customization of plastics to meet the requirements of diverse industries and applications.

It's essential to acknowledge that while additives offer numerous functional benefits, some of them may have adverse implications for human and animal health, and the environment. For instance, Brominated Flame Retards (BFRs), commonly employed to enhance the fire resistance of plastics, have been associated with environmental contamination and potential health risks[3].

The quantities of additives present in plastics can vary significantly, depending on the intended purpose and desired characteristics of the plastic product. Plasticizers, for example, are frequently used to increase the flexibility and durability of plastics, often making up a substantial proportion of certain plastic products.

Why assess additives leakage?

Plastic is a versatile material that possesses properties such as lightness, pliability, and the ability to be shaped for a wide range of applications. For this reason, it has become an integral part of modern society, revolutionising various industries, and enhancing daily lives. However, the widespread use of plastics has led to an alarming issue: the accumulation of plastic waste in the environment. Researchers estimate that over 12 Mt of macro and microplastics leak into the ocean every year[4].

There are two levels of the plastic pollution issue to be considered. First is the direct leakage of plastics into the environment, with a physical hazard for flora and fauna occurring as a result (e.g. plastics are consumed by many animals with serious health consequences such as suffocation, food dilution and more). A second level of pollution occurs due to the fact that plastics are heavily treated with chemical additives to fit them for purpose and aesthetics, and these substances can also create a chemical hazard when leached into the environment. It has been confirmed that plastic items can release numerous chemicals as they degrade over time, including plasticisers, flame retardants, stabilisers, and colourants.

On average, studies show that additives account for over 7% of primary plastic production (non-fiber) by mass[5]. Although these chemicals - over 13'000 and counting - play a crucial role in enhancing the functionality and performance of plastics, at least 24% may pose potential risks to ecosystems and human health when they enter the environment[6] [7] [5].

Consistent with the ongoing trends in plastic production and since they are now an integral component in almost all plastic manufacturing, the market for additives is anticipated to continue expanding[6] [8].

This despite the potential for significant environmental and health hazards, and as previously mentioned, there is a considerable lack of study on the scale of plastic additives leakage. This impedes the creation or improvement of risk assessment procedures and consequential regulatory mechanisms; effective recycling of plastics is also negatively impacted by the presence of additives[6] [7] [8].

This study's authors believe that understanding the extent and impact of additive contamination in the environment is of paramount importance for effective risk assessment and the development of mitigation strategies. These are the primary motivations behind this study which aims to estimate the annual total leakage of additives into the ocean and terrestrial environments from plastic products.

2.3 Scope and Study Approach

The leakage of chemicals from plastic materials can occur during various stages of their life cycle, including during production, use (like washing textiles or the wear and tear of tyres), and disposal.

The leakage of chemicals from plastic materials can occur during various stages of their life cycle, including during production, use (like washing textiles or the wear and tear of tyres), and disposal. The primary focus of this report is on quantifying the release of plastic additives into the environment, particularly during the end-of-life phase, and in some specific cases, during use – aspects that represent distinctive facets of the plastic pollution challenge.

The research methodology used in this report relies on mathematical modelling firmly grounded in the science of plastic footprinting. The method calls for calculating the amount of plastic waste generated, establishing estimates for subsequent leakage of the waste into the ocean and land, and then assessing the corresponding volume of additives also likely to have been leaked. Additionally, for two product categories, textiles and tyres, the release of additives during use are estimated, specifically as primary microplastics.

Importantly, the investigation has not included the rates at which individual chemicals leach during usage or disposal, such as migration from materials in contact with food, direct contact with skin, or inhalation or ingestion pathways.

To carry out this study, pertinent data from scientific literature and technical reports was collected and reviewed, focusing on the quantity and types of additives produced, their utilisation, and the rates at which they are incorporated into plastic products. Furthermore, data on the production volumes and management of plastic waste was gathered from the PLASTEAX database (EA – Earth Action, 2023 [12]). This database provides insights into plastic packaging production, management, and the subsequent release of plastics into the environment, with a specific emphasis on oceans and other waterways.

This study investigates how additives are employed, particularly across various sectors and polymer types. By tracing the fate of these additives within products, and global plastic waste management practices, the extent of additives leakage into the ocean and land could be estimated. This approach is supported by research showing that additive leaching can commence within the first few weeks after plastic enters the environment [13] [14] [15].

Depending on polymer type, usage sector, and end-of-life pathway, the additives are traced under three assumptions: 1) they are introduced at the production stage, 2) all produced additive quantities are utilised (there is no leftover stock), and 3) they follow the polymer's fate.

Due to ongoing knowledge and data gaps, several challenges were encountered in the course of the study preventing more granular and accurate estimates, including:

Complexity of Additive Tracing: The incorporation of additives at various stages of the plastic life cycle (e.g. production, conversion, recycling), makes it challenging to trace additive origins. Additionally, the lack of specific chemical information in different plastic products hinders research and the development of targeted solutions to limit impacts.

Limited Understanding of End-of-Life Scenarios: Another significant gap is the limited understanding of how plastics from several sectors such as construction, industrial products, electronic products, and agriculture reach their end-of-life. This lack of data hampers the ability to create accurate models for plastic pollution tracking and effective corresponding waste management and pollution mitigation strategies.

Complexity in Quantifying Leaching and Environmental Interactions: Estimating chemical leaching during use and in natural environments proves extremely challenging due to multiple variables like environmental conditions and substance interactions. Equally complex to assess are the pathways of plastic decomposition and substance transformations under specific conditions.

This report therefore also serves as an appeal for additional research and reporting on plastic additives.

2.4 Results for All Plastics

Every year, a significant volume of plastic products become waste. When waste volumes exceed the functional and operational capacity of waste management systems, recovery and recyclability are impeded, with leakage subsequently occurring as a result.

The possibility of establishing a circular system for plastics is also greatly limited by the imbalance between plastic waste volumes and waste management system capacity.

Currently plastic waste brings with it a significant quantity of additives, estimated to be 27 Mt annually.

The strength of this study's model is in using waste generation data to establish estimates for the amount of additives leaking into the environment. These estimates incorporate variations in specific sectors and polymer types.

Data on the percentages of additives added to plastic by polymer type were compiled through an examination of available studies and reviews on plastic additives. Notably, over 98% of all additives are utilised in just four polymers: PVC, PE, PP, and Styrenics. These polymers are common materials used abundantly across various industries and applications. The construction sector uses the greatest volume of the four main polymers, followed by industrial products and packaging [16].

This study reveals that up to 971kt of additives used in plastics, including textiles and tyres, find their way into marine ecosystems each year, with an additional 5'650kt leaking into terrestrial areas. This leakage occurs through various pathways, usually as a result of inadequate waste collection systems, littering, and improper disposal of plastic products. Once in the marine environment, additives can have detrimental effects on aquatic life, ecosystem health, and human well-being as they enter the food chain through bioaccumulation and biomagnification processes.

Projections indicate that without significant changes in plastic production rates, chemical composition, or improvements in waste management practices, the annual leakage of plastic additives into oceans and waterways would be expected to increase over 50% by 2040.

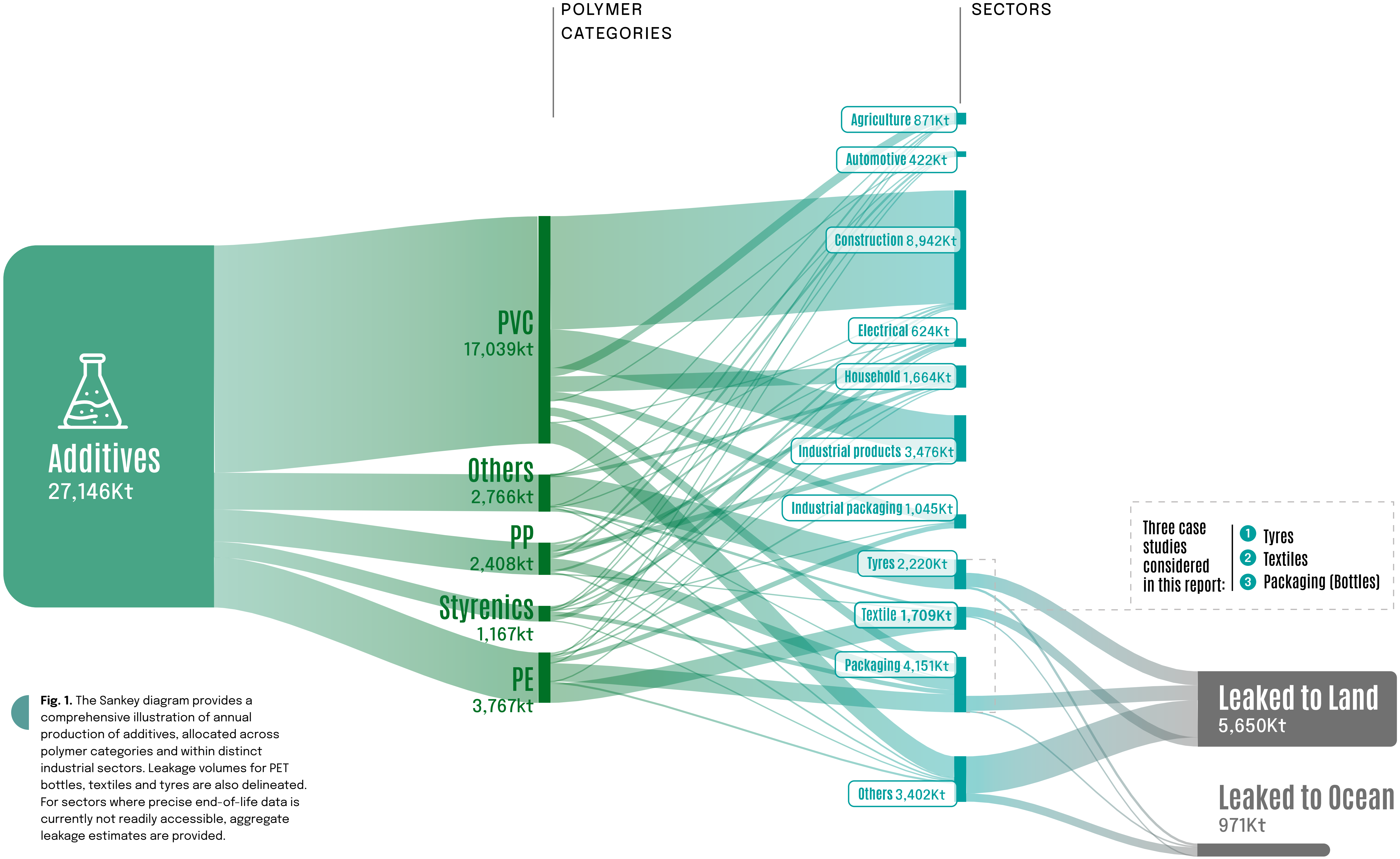


Fig. 1. The Sankey diagram provides a comprehensive illustration of annual production of additives, allocated across polymer categories and within distinct industrial sectors. Leakage volumes for PET bottles, textiles and tyres are also delineated. For sectors where precise end-of-life data is currently not readily accessible, aggregate leakage estimates are provided.

2.5 Case Studies

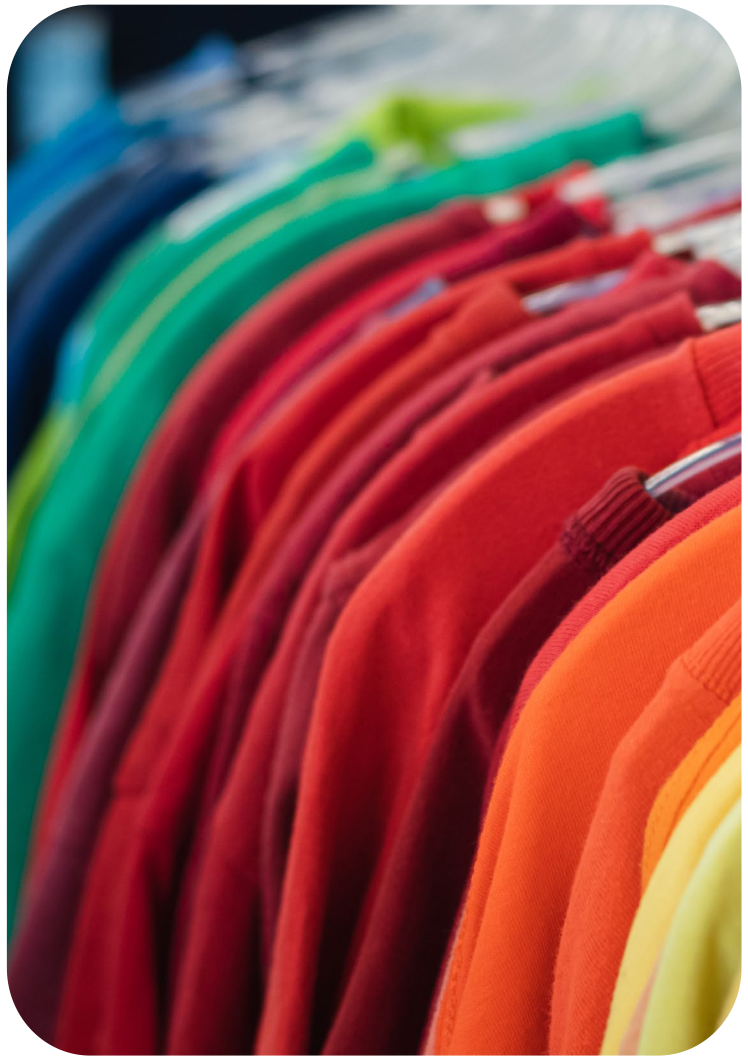
As previously mentioned, plastics are widely used in every sector, but three cases – PET bottles, textiles and tyres – have drawn the authors' attention, as these applications have high mismanage rates and/or great material losses during usage as further explained below.

Case 1 - PET Bottles:

PET bottles are a now universal vehicle for packaging consumable products, usually drinks. Generally, quantities of additives that migrate from packaging material into consumables during use are relatively small when considered in absolute terms. However, these levels remain a subject of concern due to potential implications for human health and the environment when the product reaches its end-of-life. Research indicates that approximately 116 kt of additives, out of a total of the 4'151 kt produced for packaging materials, are discharged into the ocean and 1'122 kt into terrestrial environments due to waste mismanagement. In the context of PET packaging, a substantial 830 kt of additives are used in bottles. Consequently, an estimated 13 kt of PET bottle additives enter oceans and waterways annually with another 195 kt leaking into land due to improper disposal.

Case 2 - Textiles:

Research highlights the significant environmental impact of textiles, with an estimated 522 kt of synthetic microfibers entering oceans annually during the use phase of textiles [17]. The study therefore estimates that 27 kt of additives are dispersed into the ocean and 1 kt to land each year from synthetic textile use. The problem is exacerbated by ever-increasing clothing production and the prevalence of fast fashion, with up to 14 Mt of synthetic textile waste entering the environment annually. This is equivalent to nearly 50% of total synthetic textile production and is contributing to the release of 37 kt of additives into the ocean and 697 kt to land when these products reach their end-of-life. The total release of additives from synthetic textiles during the use and end-of-life phases is estimated to be 64kt annually.



Case 3 - Tyres:

The issue of plastic pollution stemming from tyre road wear particles (TRWPs) is increasingly recognized as a significant concern in urban environments. Among all the sources of microplastics waste in Europe, in fact, automotive tyres are one of the biggest contributors with more than 500 000 tonnes of microplastics generated each year [18]. Beyond rubber and fillers, tyres contain additives crucial to functionality, including vulcanization accelerators, activators, plasticizers, processing aids, and antioxidants [19]. Several studies revealed the widespread presence of these tyre additives in soil both during use and at the end of life. The estimates indicate that tyres contribute 1043 kt of leakage to land and 177 kt of leakage to the ocean, the majority of which - 142 kt - comes from shedding during use.

2.6 Impact

It is well established that chemical compounds in plastics pose significant hazards to the environment and human well-being, causing disease, cognitive impairments and even fatalities.

Beyond the impact on individuals, there are corresponding societal implications including diminished economic productivity and increased carbon dioxide (CO_2) emissions. Minderoo has released staggering estimates for the financial consequences of certain plastics[1]. Their 2023 report estimates that in 2015 the US lost US $920 billion from disease, disability and death associated with just three plastic-associated chemicals PBDE, PBA and DEHP.

This study builds on prior assessments of plastics' risks, specifically reviewing the impact of additives on human health and the environment.

On the human side, although regulatory guidelines establish maximum allowable levels of additives in various materials, scientific investigations have revealed that additives used in materials approved for food contact, medical equipment and garments have the propensity to migrate, potentially posing toxicity risks to human health. Moreover, occupational exposure during production and disposal of plastic items has been shown to pose risks to human health.

Plastic particles are now ubiquitous in water and soil and the impact of plastics on the environment is being widely investigated. The presence of plastics and additives creates both sources and vectors of environmental pollution, disrupting ecosystems and food chains. For example, recent research reveals that physical turbulence significantly amplifies the leaching of additives, such as phthalates from plastic particles, into aquatic environments. Numerous studies have also documented the presence of plastic additives in agricultural soil, including plasticizers, antioxidants, and stabilisers. As an example, research has shown that Bisphenol A (BPA) can be introduced into the soil environment through sludge and effluent discharge, or from municipal waste disposal sites [1] [20].

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2.7 Conclusions and Ways Forward

Every year, plastic products become waste and with that approximately 27 Mt of plastic additive waste is generated.

This study finds that almost 1Mt of additives used in plastic find their way into marine ecosystems and over 5.6 Mt to land annually. The sources of the additives leaking into the ocean are primarily packaging (~116 kt), synthetic garment textiles (64 kt released between the use phase and end-of-life) and tyres (177 kt, the majority of which - 142 kt - comes from loss during usage).

Leakage occurs through various pathways, sometimes directly from littering or leakage during use, but also due, for example, to the absence of adequate waste collection systems or improper disposal.

Once in the marine environment, additives can have detrimental effects on aquatic life, ecosystem health, and even human well-being. These effects are often due to additives entering the food chain through bioaccumulation and biomagnification processes. This suggests that the environmental impact of the plastic additives might be of higher concern than the plastic polymers themselves.

The projections indicate that without significant changes in plastic production rates, chemical composition, and improvements in waste management practices, the annual leakage of plastic additives into oceans and waterways can be expected to increase over 50% by 2040.

This report further establishes that immediate action is required by the scientific community, policymakers and manufacturers to address the causes of additives leakage and protect global ecosystems from further pollution.
There are several specific recommendations for pollution-mitigating interventions that have emerged during this study.

1

Polymer Selection: selecting polymers that are easily reusable, recyclable, or biodegradable is central to reducing plastic waste, ultimately fostering and enabling a more sustainable and circular model for plastics.. Additionally, simplifying product designs and minimising the use of different polymers can enhance recycling efficiency and improve the quality of recycled materials.

2

Reduce Reliance on Virgin Plastics: Increasing the production of high-quality recycled materials is essential to reducing the world's reliance on virgin plastics. Investment in efficient recycling technologies ensures that the output of the recycling process meets stringent quality standards, making it a vital step toward sustainable plastic management.

3

Reduce Problematic Additives: To specifically address additive leakage, a key strategy is to prioritise the reduction or substitution of problematic chemical compounds. The critical first step to inform decision-making and immediate reductions is establishing a comprehensive list of problematic additives, considering both their direct and indirect impacts. This list should be actively managed and kept up to date so that new molecules and substances can be added as research on additives continues.

4

Expand Additives Research: Further research is necessary to deepen our understanding of how and when additives (and their degradation by-products) are released into the environment and human bodies, allowing us to develop effective prevention and remediation strategies.

5

Minimise Hazards and Exposure: Minimising chemical hazards and exposure at both the production and end-of-life stages is paramount. Thoughtful chemical selection and evaluation can help mitigate the potential environmental and health impacts associated with plastic production and disposal.

6

Delineate Essential Plastics: Recognizing the indispensable role of plastics in our modern world, particularly in critical applications such as medical devices and infrastructure materials, it becomes essential to distinguish between essential and non-essential plastic items. Stricter regulations, encompassing both polymer selection and chemical scrutiny, hould be applied broadly, but especially for non-essential products.

7

Align Polymer Usage with Waste Management Capabilities: Addressing plastic pollution entails aligning polymer selection with local waste management systems to maximise the efficiency of plastic waste processing. Effective waste management practices, combined with measures to mitigate littering, are crucial for minimising the environmental risks posed by plastic additives.

8

Enhance Chemical Content Transparency: Expanded transparency for the chemical composition of plastic products is vital to protecting human and environmental health. Clear and accessible information empowers consumers, regulators, and stakeholders to make informed decisions, ultimately fostering accountability and driving the adoption of safer alternatives.

In conclusion, a multifaceted approach is necessary to confront the complexities associated with plastic additives. This includes ongoing research and scientific investigation, regulatory interventions, and fundamental shifts in the use and management of certain additives. By incorporating these considerations into plastic design and management, we can move toward a more sustainable and environmentally-responsible approach to plastic waste, reducing the negative impacts on nature and human health.

3 Detailed Results

3.1 Introduction, Plastics - A Double-Edged Sword

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Plastic is a versatile material that possesses properties such as lightness, pliability, and the ability to be shaped for a wide range of applications. For this reason, it has become an integral part of modern society, revolutionising various industries, and enhancing daily lives. However, the widespread use of plastics has led to an alarming accumulation of plastic waste in the environment. Researchers estimate that over 12 Mt of macro and microplastics leak into the ocean every year [4].

On average, additives account for over 7% of the primary plastic production (non-fiber) by mass[5] and a ground-breaking study in 2021[7] showed that among 10'000 plastic related substances, over 2'400 were identified as substances of potential concern, as they meet one or more of the persistence, bioaccumulation, and toxicity criteria in the European Union.

More recently in 2023, a report by UNEP combined the results of two studies[7][21] and updated the global picture: concluding there are over 13'000 different substances that are used in plastic as plasticizers, fillers, heat stabilisers, and for other purposes. Of these, 7'000 distinct chemicals have been screened for their hazardous properties, of which more than 3'200 plastic monomers, additives, processing aids, and non-intentionally added substances have been identified as chemicals of potential concern based on their hazardous properties. Some additives, such as brominated flame retardants, can be harmful even in very small quantities, with the potential to cause severe damage to environmental and human health.

The picture is far from complete, as more studies are being conducted, but currently, it appears that around 24% of the additives used in plastic are of potential concern[6] [7] [5] [21].

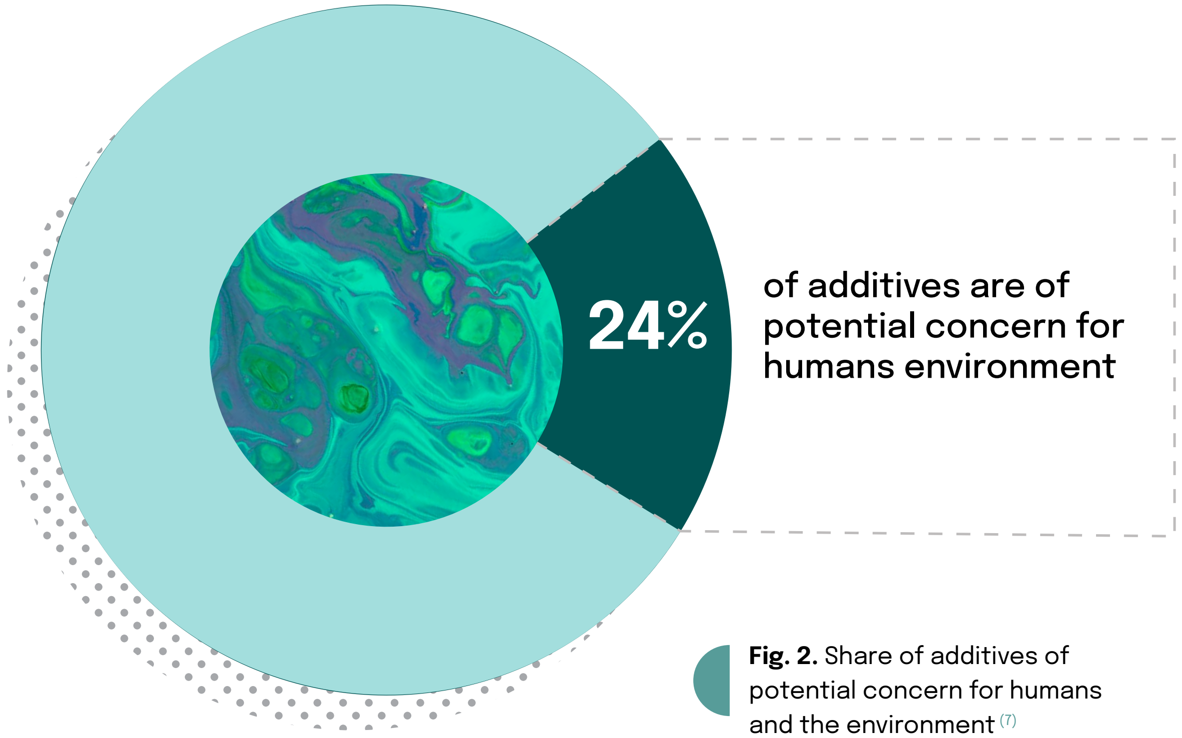


Fig. 2. Share of additives of potential concern for humans and the environment [7]

Consistent with the ongoing trends in plastic production and since they are now an integral component in almost all plastic manufacturing, the market for additives is anticipated to continue expanding[6][8].

While extensive research has been conducted on plastic materials, limited attention has been given so far to the information on the nature and the quantity of additives that are carried along the plastic life cycle. Additives are, in reality, an inseparable part of the plastic production pipeline, but despite their environmental and health hazard, there is a lack of comprehensive study on the scale of leakage of the additives used in plastic products. This impedes the creation or improvement of risk assessment procedures and consequential regulatory mechanisms; the effectiveness of plastic recycling is also significantly impaired by the presence of additives[9][10][11].

In line with the increased recognition and understanding of how plastic additives contaminate the environment, this report aims to establish a foundation for constructive dialog around the issue and identification of opportunities to mitigate negative impacts to the environment and human well-being.

3.2 Scope, Approach of the Study and Data Gaps

Scope

The impact of chemicals in plastic is a prominent scientific topic and numerous recent reports have contributed to greater understanding of related issues (e.g.[1][22]).

This study takes a unique approach and aims to provide a novel perspective on the impact of plastics on the environment. The leakage of chemicals from plastic materials can manifest at various points along their lifecycle, including production, usage (e.g., laundering of textiles or tyre wear and tear), and disposal. This study focuses specifically on quantifying the leakage of plastic additives in the environment from plastic products that have reached their end-of-life. In several cases the leakage of plastic additives during use was also explored.

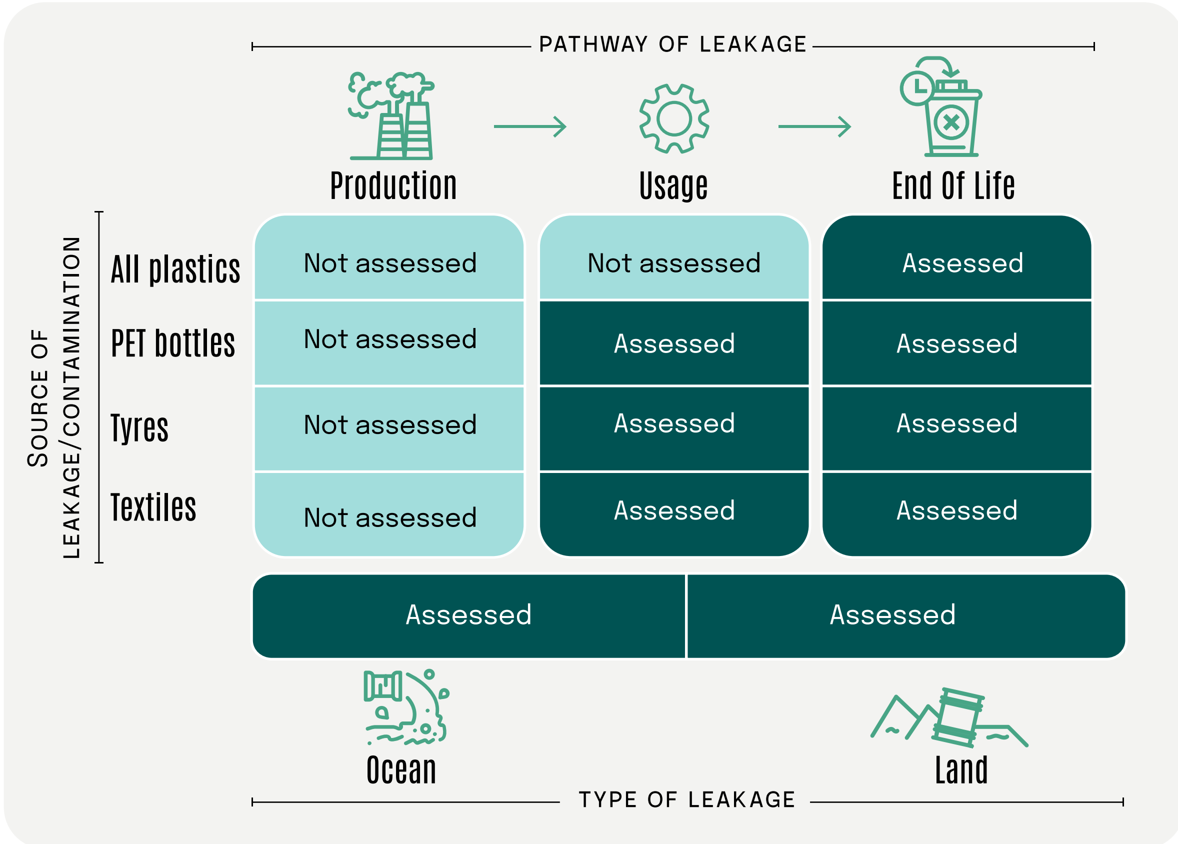


Fig. 3. The figure illustrates the scope of the current study.

Approach

This research adopts a mathematical modelling approach rooted in the science of plastic footprinting. The aim of plastic footprints is to calculate plastic waste volumes and by extension the volume of associated additives that are at risk of environmental leakage from plastic waste, as was the focus of this study. This examination also estimates leakage occurring during the use of two plastic product classes, textiles and tyres, with a specific focus on microplastics.

It is noted that this study does not examine leaching of individual chemicals during usage or disposal, such as migration from food contact materials or direct skin contact and inhalation or ingestion pathways. The leaching during usage is influenced by multiple factors (temperature, time, light etc.) and requires more in-depth study.

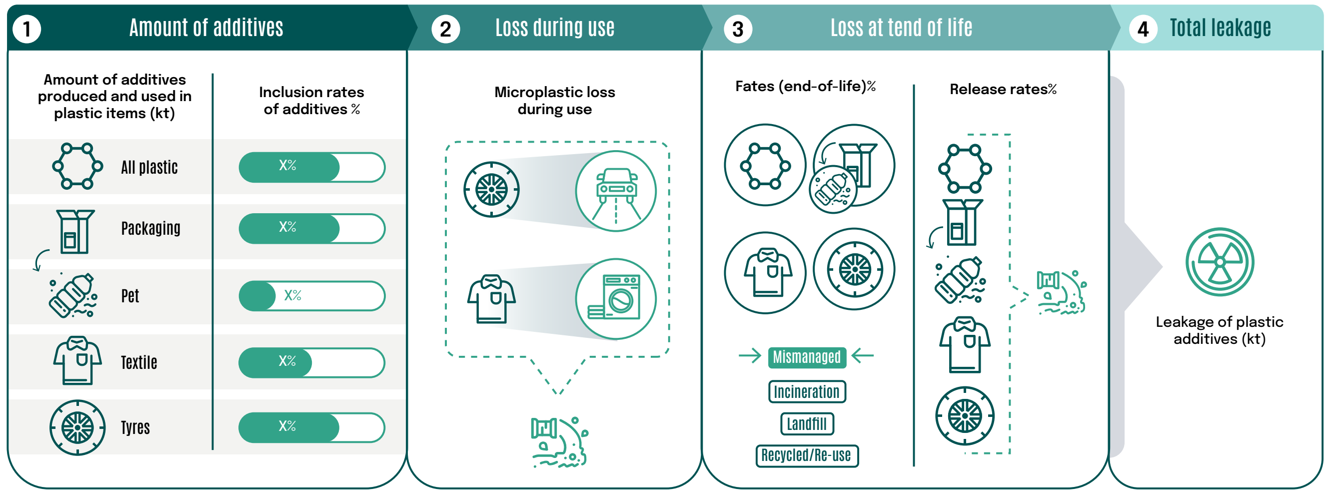


Fig. 4. Diagram of approach used to follow the fate and leakage of additives through product use and end-of-life phases.

To achieve the study's objectives, pertinent data from scientific literature was systematically collected and reviewed together with technical reports concerning the production quantities and types of additives, their incorporation into various polymers, and their usage across different industrial sectors. Additionally, data on plastic waste generation and management was gathered from the comprehensive PLASTEAX database (EA - Earth Action, 2023[12]). This extensive database offers insights into plastic packaging's production, management, and the leakage thereof, with a special emphasis on oceans and other water bodies, including lakes, rivers, and groundwater. This approach enabled the researchers to assess the extent of leakage of additives to both ocean and land.

Fig. 5. The diagram shows the plastic flow, from waste production to leakage.

Therefore, this study primarily models the fate of chemical additives entering the ocean as a result of their inclusion in plastic products and the mismanagement of those products. This choice is informed by research suggesting that, upon entering the environment, leaching occurs within the initial weeks[14][15].

The approach employed to estimate the leakage of additives into the environment, with potential repercussions for both human health and the environment, as mentioned, follows these additives together with the plastic products.

Depending on polymer type, usage sector, and end-of-life pathway, the additives are traced under three assumptions:

1) They are introduced at the production stage.(*)

2) All produced additive quantities are utilised - there is no leftover stock.

3)They follow the polymer's fate.

Specific attention is paid to the use phase only for two product categories: textiles and tyres.

* Additives can be added at very different steps of the plastic life cycle (production, conversion, recycling etc) making the traceability very difficult. There is a lack of knowledge regarding which chemicals are present in which products, which makes it difficult to research and find appropriate solutions to the problem.

Data gaps

Several challenges arose during this study. First of all, the fact that additives are incorporated at various stages of the plastic life cycle, including production, conversion, and recycling, makes it challenging to trace their origins. Additionally, the lack of specific chemical information in different plastic products hinders research and the development of targeted impact-mitigation solutions.

Wide ranges of inclusion rates are also observed in general plastics (the shares highly depend on the specific application)[9]. This creates significant difficulties for accurate quantification of the additives that are present in the sold products.

Despite the existing data gaps an examination of the most comprehensive studies and reviews on the topic has allowed for the mapping of additives added to plastic by polymer, and it is seen that over 98% of all additives are used in 4 main polymers: PE, PP, PVC, and Styrenics[16].

Therefore for the purpose of this report, the content of additives in 5 main categories of polymers has been considered: PE Polyethylene, PP Polypropylene, PVC Polyvinyl Chloride, Styrenics and others miscellaneous (including Acrylonitrile-Butadiene-Styrene, Polycarbonate for non-fiber plastic but also polystyrene, polyamide for textiles and rubber for tyres). Those polymer categories alone represent 98% of all the additives used in 10 large sectors: agriculture, automotive, construction, electrical, household, industrial products, industrial packaging, textiles, tyres and others[16][9].

Class of additives	Function	Examples	Inclusion rate
Plasticisers	Improve the flexibility, durability and stretchability	Phtalates Aliphatic Di/Tri Esters Phosphates Trimellitates	**10-70%** Andrady and Rajapakse 2019; Hahladakis et al. 2018 **20-60%** van Oers, van der Voet, and Grundmann 2012
Flame retardants	Prevent ignition and/or flame propagation	Alumina trihydrate Antimony oxide Halogenated hydrocarbons Polybromo diphenyl ethers	**10-20%** Andrady and Rajapakse 2019; van Oers, van der Voet, and Grundmann 2012 **3-25%, 0.7-3%** Hahladakis et al. 2018
Fillers	Reinforcement or reduction of cost	Calcium carbonate Clays Silica Alumina Rutile	**0-50%** Andrady and Rajapakse 2019; Hahladakis et al. 2018 **10-50%** van Oers, van der Voet, and Grundmann 2012
Heat stabilizers	Control degradation during processing	Organotin mercaptides Barium Cadmium and Zinc soaps Dialkyl maleates	**0.1-8%** Andrady and Rajapakse 2019 **0.5-3%** Hahladakis et al. 2018 **1-5%** van Oers, van der Voet, and Grundmann 2012
Antioxidants	Control oxidative degradation during exposition to ultraviolet (UV) light	Phenolics Phosphates Amines Thioesters	**0.1-2%** Andrady and Rajapakse 2019 **0.05-3%** Hahladakis et al. 2018 **0-1%** van Oers, van der Voet, and Grundmann 2012
Other Colorants, Processing aids, Anti-statics, Biocides, Impact modifiers, Lubricants, Light stabilizers, etc	Obtain the desired property in the product	N/A	N/A

Table 1. Reported inclusion rates of additives in various polymers.

Another significant gap is the limited understanding of how plastics from several sectors such as construction, industrial products, electrical, and agriculture (and others) reach their end-of-life. This lack of data hampers the ability to create accurate models for plastic pollution tracking and consequently, effective waste management and mitigation strategies.

In addition, the majority of additives enter the environment due to inadequate end-of-life management of plastic products. However, given the intricate and diverse nature of chemicals involved, it is important to acknowledge that the possibility of leaching even in instances of proper plastic management cannot be entirely ruled out, but this is not addressed in this study.

Estimating chemical leaching during use and in natural environments proves extremely challenging due to multiple variables like environmental conditions and substance interactions. Understanding leaching kinetics is critical for assessing the chemical consequences of microplastic pollution, as microplastics have become ubiquitous pollutants[13] [14] [15]. Equally complex to currently assess are the pathways of plastic decomposition and substance transformations under specific conditions.

3.3 Results for All Plastics

3.3.1 Introduction

Additives are substances incorporated into plastic during production to enhance specific characteristics, improve performance, or facilitate processing. These additives can alter the plastic's appearance, durability, flame resistance, flexibility, and more. The quantities of additives in plastic can vary significantly (Table 1 page 48), depending on the specific purpose and desired characteristics of the plastic product.

Plasticisers, for example, help make PVC more malleable and suitable for a wide range of applications, such as construction materials, medical devices, and consumer goods, and can make up to 80% of the final product. PVC also contains large quantities of Quaternary Ammonium Compounds (QACs), which are commonly employed as biocides and preservatives but have been found to have toxic effects on aquatic organisms and can persist in the environment for extended periods of time [16].

By reviewing the most comprehensive studies and reviews on the topic, the percentages of the additives added to plastic by polymer have been mapped, with over 98% of all additives appearing in 4 main polymers: PVC, PE, PP and Styrenics [16].

From this research it appears that the largest quantities of additives in plastic are typically used to produce PVC products (73% of total additives production) followed by PE and PP together representing over 20% of annual additives production.

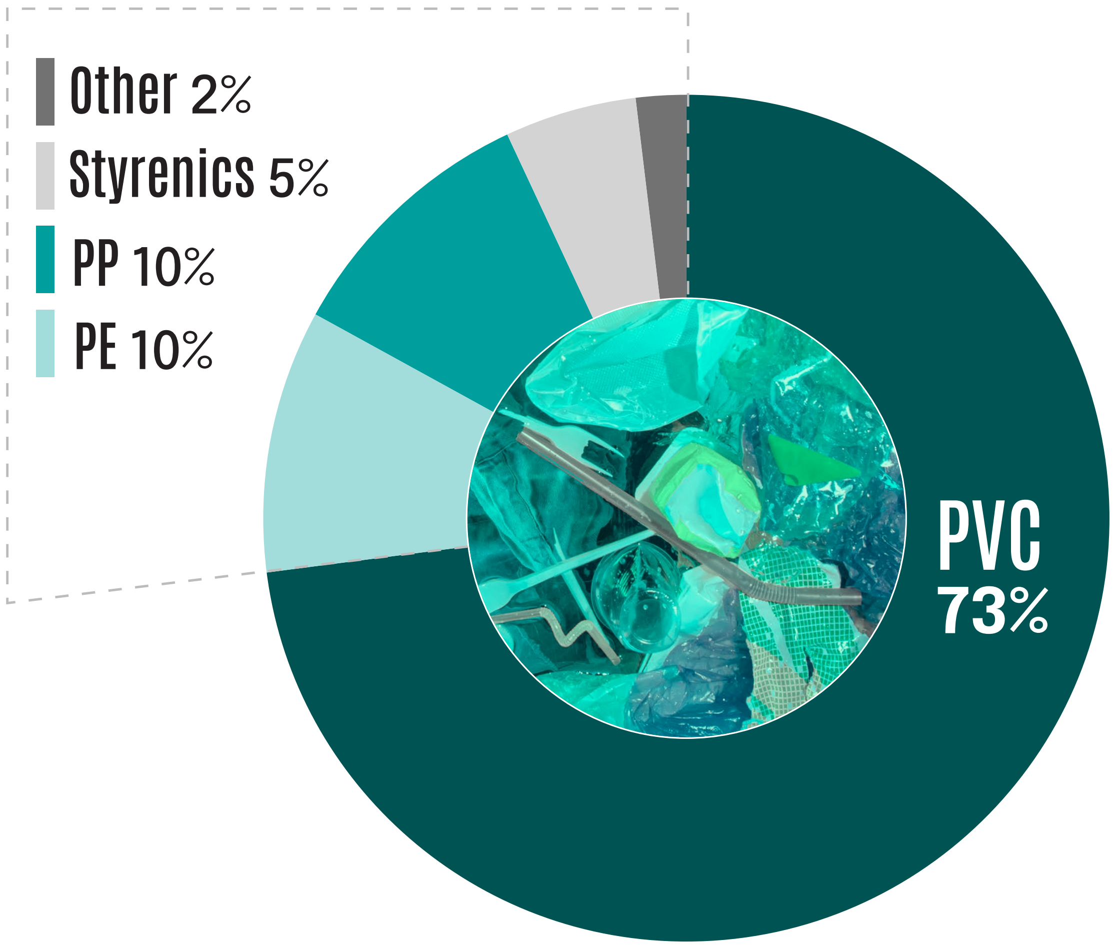


Fig. 6. Shares of the total amount of additives used by polymer, expressed in % w/w [15]

These common polymers appear regularly in the materials utilised in various industries and applications, and as a consequence, large quantities of additives end up being found in the construction sector (47%), followed by industrial products (17%) and packaging (14%) [16]. The additives in construction and industrial products for example, are largely used in insulation materials, plastic films, and door and window frames, among other products. These additives are incorporated to improve the thermal efficiency, structural integrity, and overall performance of the plastic-based construction products. In packaging, additives are typically added to provide flexibility, colouring, and durability against heat or sunlight.

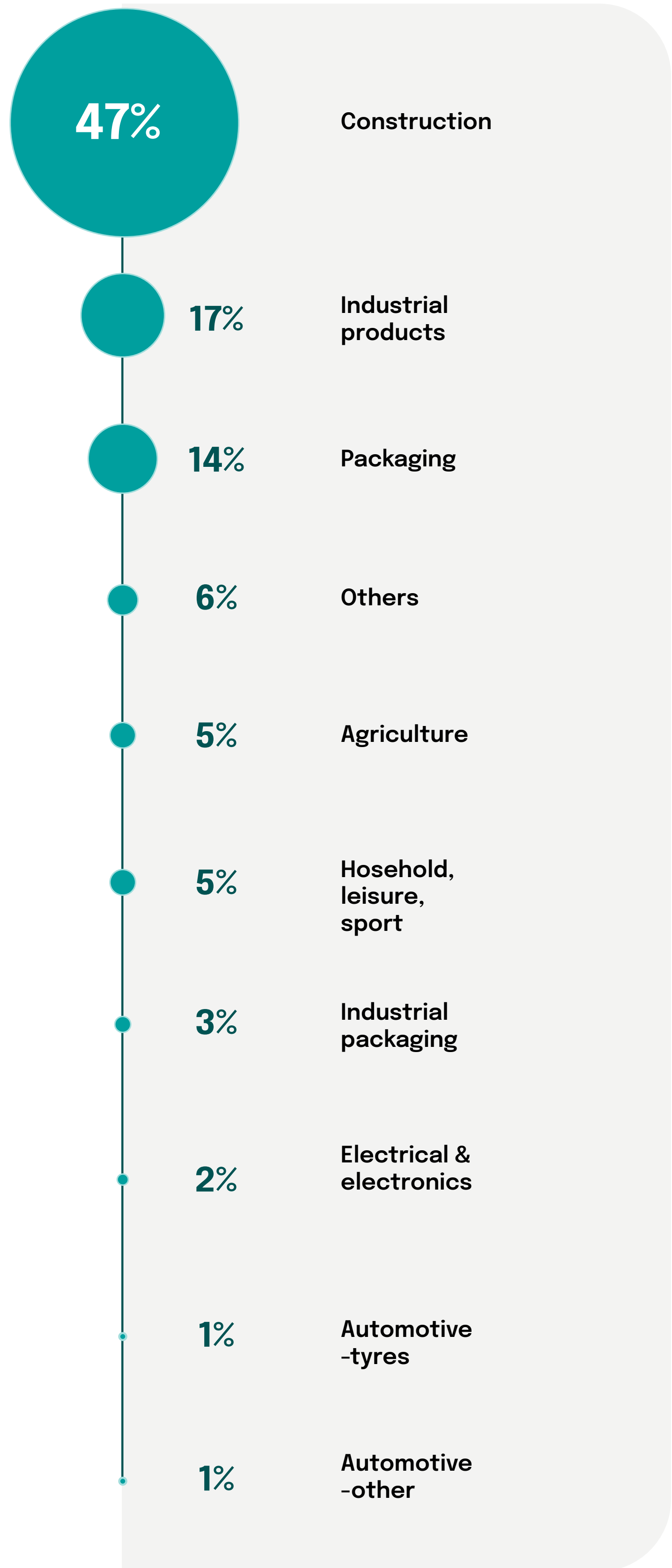


Fig. 7. Shares of total additives produced and used by various sectors. [16]

Every year, a significant volume of plastic products become waste. When waste volumes exceed the functional and operational capacity of waste management systems, recovery and recyclability are impeded, with leakage subsequently occurring as a result. The possibility of establishing a circular system for plastics is also greatly limited by the imbalance between plastic waste volumes and waste management system capacity. With the plastic waste, comes a significant quantity of additives, approximately 27 Mt (million tons) annually.

The strength of the model in this study is the use of waste management data, particularly mismanagement assessments, to track the quantities of additives produced and used in plastics, tracing their redistribution within polymers and sectors, and finally how their end-of-life will lead to leakage in the environment, in particular into the ocean and terrestrial areas.

The Sankey diagrams - here for all plastics, and further in the report for the specific cases of PET bottles, Textiles and Tyres - visually illustrate the intricate flow of additives, from production to their release in the ocean and land. The table provides an overview of all additive losses estimated throughout this study.

	Use		End of Life		Leakage	
	OCEAN	LAND	OCEAN	LAND	OCEAN	LAND
All plastic	N/A	N/A	971 kt	5650 kt	971 kt	5650 kt
Packaging	N/A	N/A	116 kt	1122 kt	116 kt	1122 kt
Pet	N/A	N/A	13 kt	195 kt	13 kt	195 kt
Textile	27 kt	1 kt	37 kt	696 kt	64 kt	697 kt
Tyres	142 kt	384 kt	35 kt	659 kt	177 kt	1043 kt

Table 2. The table summarises all the results obtained in this study with the quantities of additives leaked at each step.

Many additives are used in plastics in different sectors and will end up in the ocean and waterways.

POLYMER CATEGORIES

SECTORS

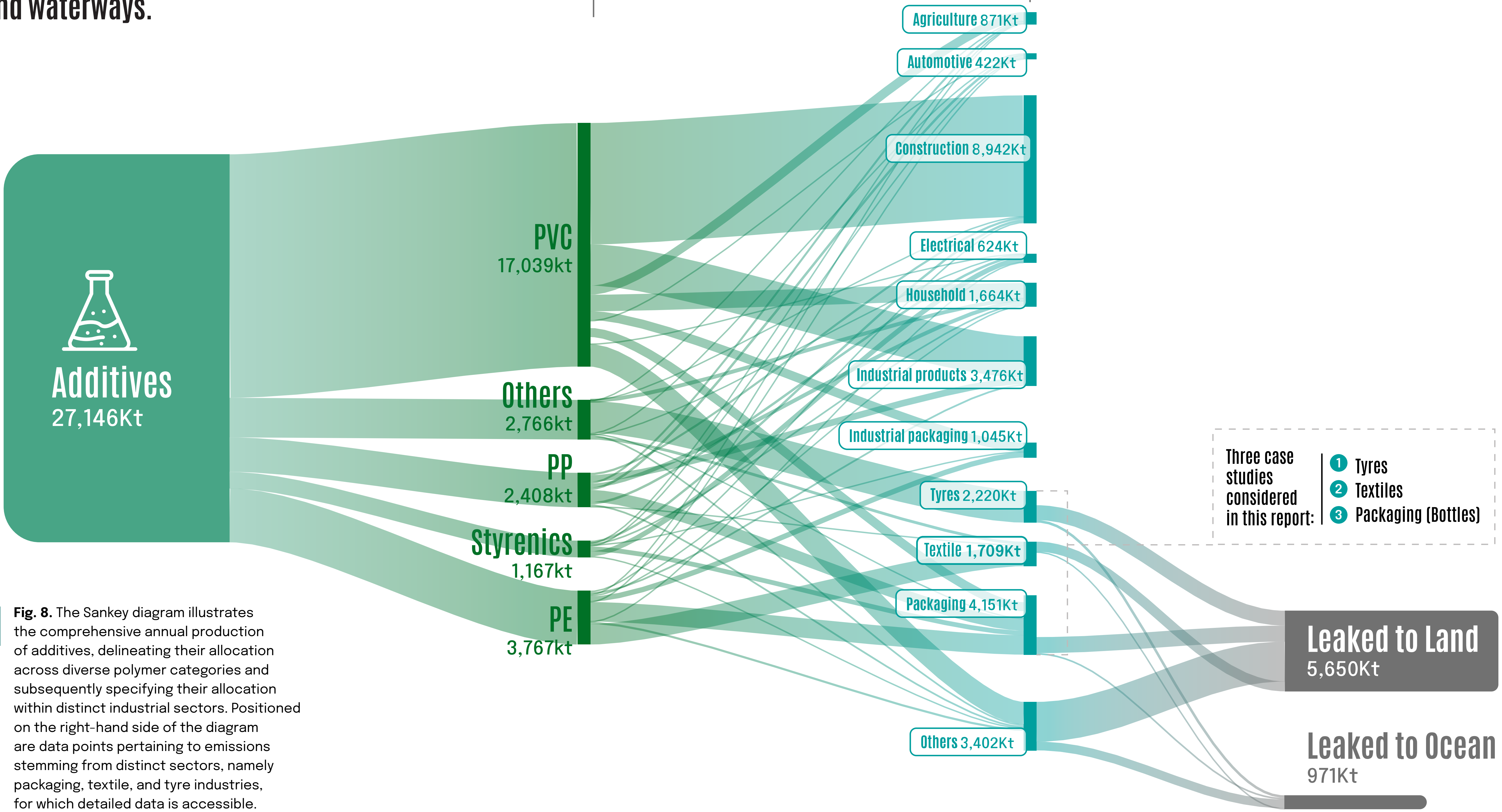


Fig. 8. The Sankey diagram illustrates the comprehensive annual production of additives, delineating their allocation across diverse polymer categories and subsequently specifying their allocation within distinct industrial sectors. Positioned on the right-hand side of the diagram are data points pertaining to emissions stemming from distinct sectors, namely packaging, textile, and tyre industries, for which detailed data is accessible. Furthermore, it provides an aggregate representation of emissions estimated from other sectors, where precise end-of-life data is currently not readily accessible.

3.3.2 Results

3.3.2.1 Amount of Additives

At the beginning - left side - of the diagram, we see that a total of 27'146 kt of additives are produced annually. These calculations consider the total amount of plastic production (non-fibres) for the year 2021, with additives appearing to have an average inclusion rate of 7%. This quantity has been consequently redistributed by classes of polymers (five polymer categories: PP, PVC, PE, Styrenics, and others) and sectors (agriculture, automotive, construction electrical, household, industrial products, industrial packaging, textiles, tyres, and others), and can be followed though the Sankey diagram.

3.3.2.2 Loss During Use

N/A

3.3.2.3 Loss at End-of-Life

N/A

3.3.2.4 Final leakage

Overall, the study estimates that, considering the cumulative leakage in the environment due to usage and the eventual disposal of plastics across various sectors, up to 971 kt of plastic additives potentially enter the ocean and 5'650 kt enters terrestrial environments each year.

The packaging, textiles and tyres sectors, are known to pose substantial threats for environmental leakage due to littering or abrasion and often poor management at their end-of-life. These realities have been covered in numerous studies and the consequential contribution to plastic leakage into the environment is well-investigated.

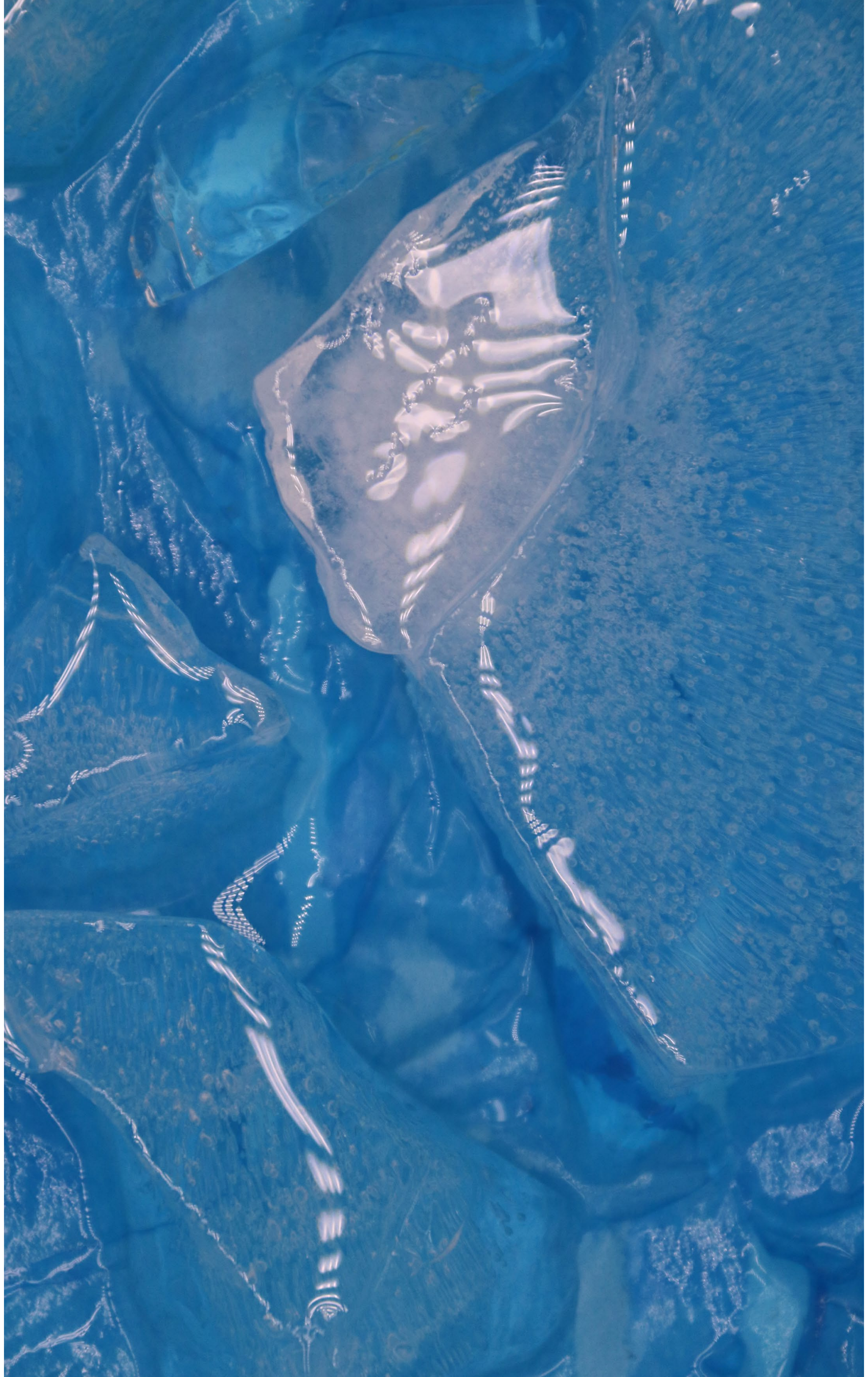
For other sectors, including industrial, agricultural and construction, there is a significant lack of information regarding both plastic leakage during use and end-of-life fates for discarded products.

Therefore, the present analysis provides an overall view on total additives leakage for all plastic products, and places a specific emphasis on three sectors: packaging (with a focus on PET bottles), textiles, and tyres. Collectively, these sectors contribute a substantial 357 kt and 2'862 kt of additives that ultimately find their way into the ocean and land through plastic products (more details in the respective case study - chapters A, B and C).

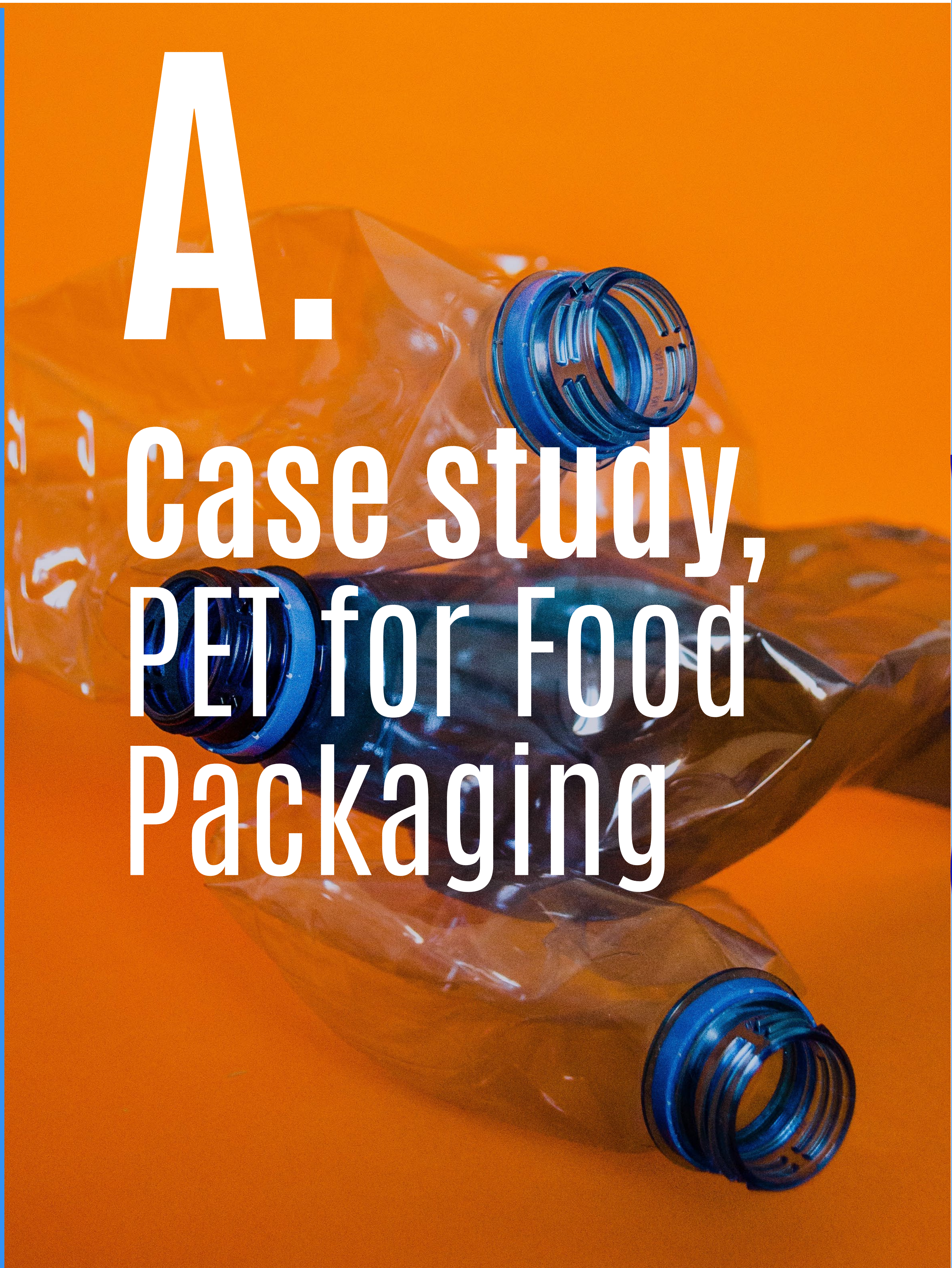
The remaining volume of leaked additives is attributed to the other sectors, for which, as mentioned, there is a lack of sufficiently detailed data. Therefore the analysis cannot offer a breakdown of how these additives reach or are managed at the end-of-life.

In addition to specific estimates, the model helps in establishing that inaction will greatly affect natural and human ecosystems. Based on plastic production trends and without significant improvements to current waste management practices, by 2040 the annual leakage of additives from plastic products into oceans and waterways is expected to increase annually by over 50%.

Readers are invited to recognize that this report is intended to mark the beginning of an essential conversation. While this study represents progress in understanding plastic additives and their impact, the data and calculations presented herein are not exhaustive. This study seeks to serve as a catalyst, encouraging others to join a collaborative effort, contributing additional information on diverse leakage pathways and providing more granularity to further enhance our collective modelling efforts.



A. Case study, PET for Food Packaging



A.1 Introduction - Why Examine PET?

Each year, approximately 29 Mt of Polyethylene terephthalate (PET) are manufactured, with a substantial 87% allocated to the packaging sector.

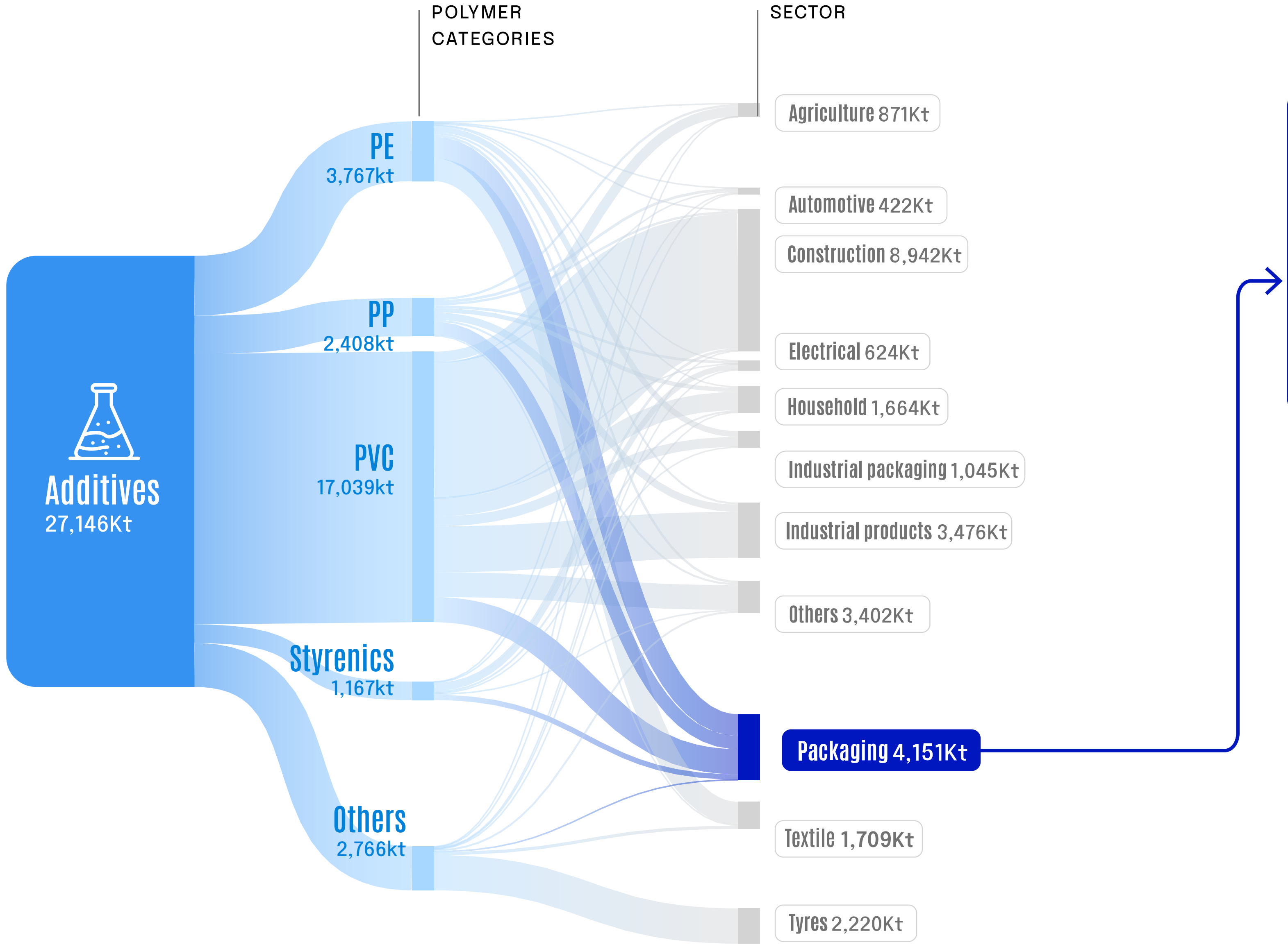
Each year, approximately 29 Mt of Polyethylene terephthalate (PET) products are manufactured, with a substantial 87% allocated to the packaging sector. PET, renowned for its light weight, durability, and recyclability, is predominantly employed in the production of drinking bottles and personal care items. During the manufacturing process, various additives can be incorporated into the polymer to achieve or enhance specific material properties. It is noted that the application of additives in PET bottles is subject to rigorous regulation by authorities including the U.S. Food and Drug Administration (FDA) in the United States, the EU Regulation 1935/2004, and analogous agencies worldwide. These regulatory bodies establish stringent safety standards to ensure that additives do not migrate from the packaging into the contents, thereby safeguarding human health. A specific migration limit into food has been set at 60 mg/kg. While PET itself is deemed safe for food and beverage storage, there is evidence suggesting that certain additives used during the manufacturing process may leach into the product, thereby raising concerns regarding safety [27].

Presently, the European Chemical Agency lists approximately 95 chemicals that are added to PET used in packaging. However, recent research has shown a more extensive spectrum of potential migratory compounds from PET plastic and polyester, totalling at least 919 substances. This expansive group encompasses not only plastic additives but also processing aids and chemical by-products, including carcinogenic agents such as antimony and cobalt[23]. Furthermore, an in-depth investigation uncovered the presence of 193 distinct chemical compounds within PET utilised for food contact materials. The results indicated that while 150 of these substances were detected in the material, only 41 were authorised for such use [24]. The identification of these substances and the elucidation of their inclusion in the material, or their migration into the packaging's contents, are often exceptionally intricate processes. These substances, generally referred to as "NIAS" or non-intentionally added substances, are acknowledged within the Framework Regulation and Plastics Regulation. Nevertheless, their safety necessitates assessment, and their regulatory status remains ambiguous.

Among the most frequently encountered non-intentionally added substances (NIAS) in PET bottles are substances like Formaldehyde, Acetaldehyde, Antimony, Propanol, Butanol, Nonanal, Glyoxal, Methylglyoxal, Acetone, Phthalates, and various carbonyl compounds resulting from PET degradation or breakdown processes. Numerous studies indicate that some of these compounds, such as phthalates and acetaldehyde, do migrate from PET bottles but are generally deemed safe for consumers [25] [26].

However, recently antimony and some other substances appear to be reopening the discussion on food storage safety with PET containers. Research published in July 2022 by the civil society organisation Defend Our revealed that 40% of PET plastic-bottled beverages tested contained antimony levels exceeding 1 part per billion (ppb), which is California's recommended limit for drinking water. This level of exposure may potentially lead to liver disease and increase the risk of cancers, heart disease, and organ toxicity. Significantly, 90% of the tested beverages exceeded an even stricter health limit of 0.25 ppb suggested by Defend Our Health, accounting for daily antimony exposures from various sources. Notably, the study found that antimony levels in food and beverages rose when PET plastic bottles and trays were exposed to heat, light, or when used for acidic beverages like juices and carbonated drinks. Additionally, there is concern about infants and toddlers who may ingest unsafe antimony levels by sucking on soft polyester items. Consequently, these findings raise significant concerns about the potential impact of PET plastics on children's health, given their routine exposure to multiple sources of antimony [27].

A.2 Results



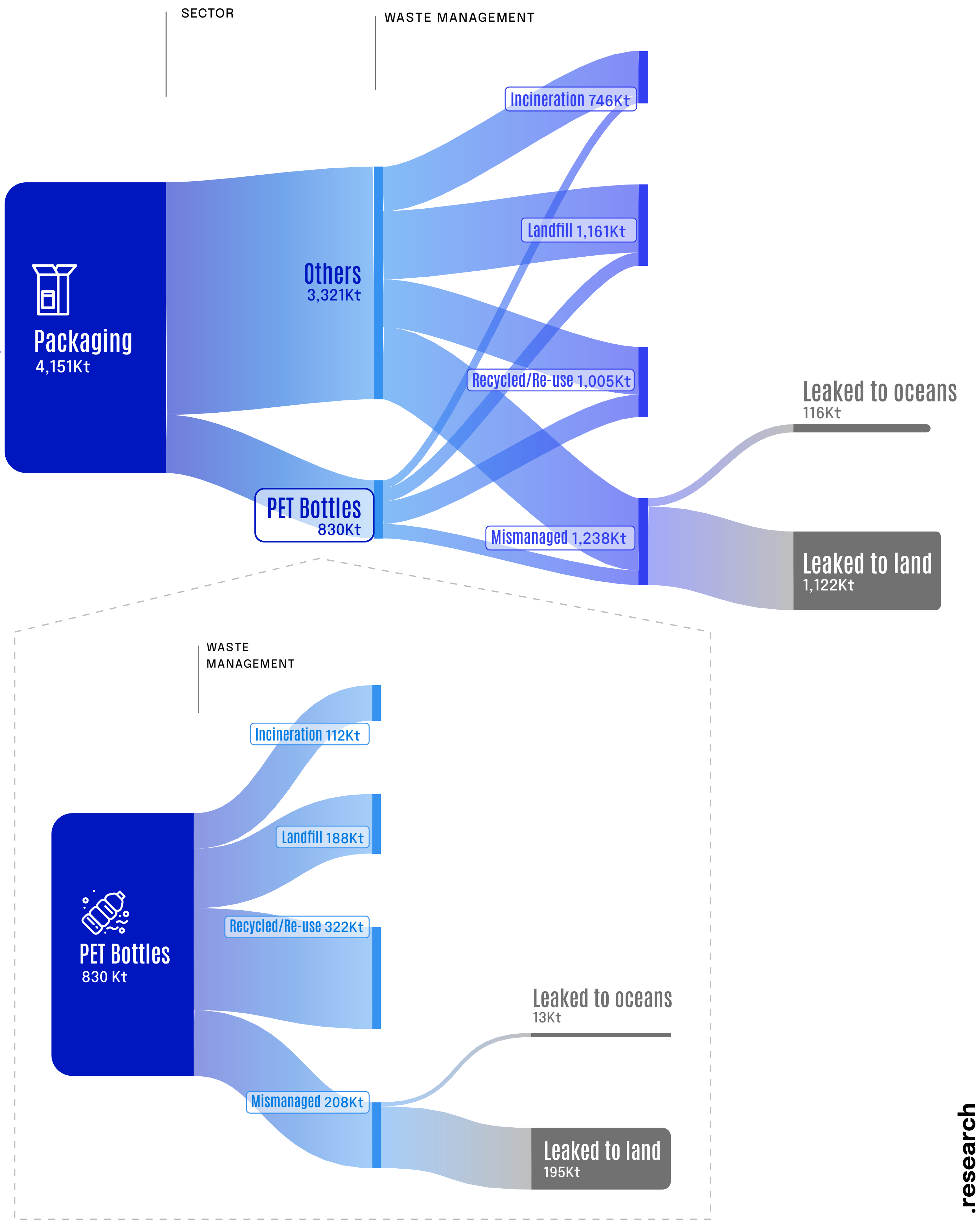


Fig. 9. The Sankey diagram shows the total yearly production of additives that the study estimates are used for packaging and PET bottles and the quantities that follow the use and the fate of the plastic items, and can eventually be dispersed in the ocean and land.

A.2.1 Amount of Additives

As previously described for "all plastic" - page 118 ad for more details Appendix 4.2 - considering the total amount of plastic production (non-fibres) for the year 2021 and the average inclusion rate for additives an estimation was obtained of the quantity of additives in plastic which was then redistributed by classes of polymers. Combining this information with the total amount of plastic used in the packaging sector by polymer, the total of additives used in the packaging totals 4'151 kt.

Out of the annual production of 29 Mt of PET, a significant 87% is allocated for packaging purposes[12], with PET bottles constituting 20% of all packaging waste. This results in a staggering 25 Mt of PET bottles becoming waste globally each year. Given that the content of additives in PET bottles is estimated at approximately 3% in mass, a substantial 830 kt of additives are specifically employed in PET bottles.

A.2.2 Loss during use

The quantities of additives that migrate from PET into food during use are relatively small when considered in absolute terms, therefore in the context of this report the amount is considered negligible. Moreover, as previously stated, exposure to additives via direct contact - ingestion, inhalation etc - is out of the scope of this report as this would be considered leaching during use and its rate is dependent on numerous parameters (temperature, time, light etc.) and it would require a separate and more in depth study.

However, these levels remain a subject of concern due to their potential implications for human health. These additives, while present in small concentrations, can still exert adverse effects, particularly when they are persistent, bioaccumulative, or toxic. Many recent studies (for example [28][29]) have already thoroughly covered the risks of chemicals migrating from food contact materials, including PET bottles.

In particular, in a ground-breaking project led by The Food Packaging Forum, a database called the Chemicals Associated with Plastic Packaging (CPPdb) was developed. This database is intended to provide comprehensive information on chemicals used in plastic packaging throughout its lifecycle. It lists 906 chemicals likely associated with plastic packaging, with 63 posing the highest human health hazards and 68 posing the highest environmental hazards according to European Chemicals Agency classifications. Additionally, 7 of these substances are classified as persistent, bioaccumulative, and toxic (PBT) or very persistent, very bioaccumulative (vPvB), and 15 are recognized as endocrine disrupting chemicals (EDC), emphasising the need for further assessment and potential substitution of these hazardous chemicals in plastics.

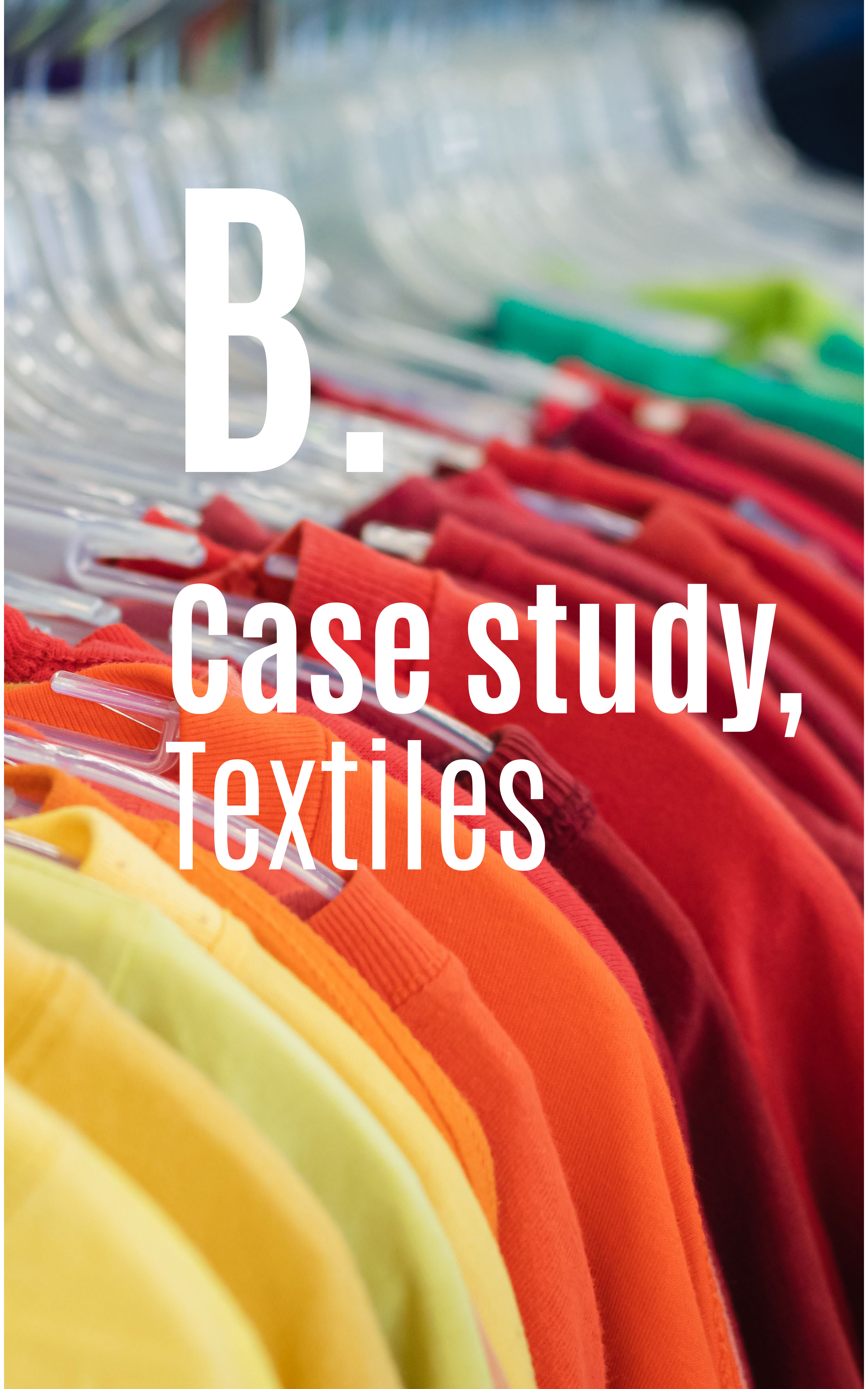
Therefore, this report refers the reader to the existing literature for the use phase of PET bottles and focuses on investigating the presence of additives released into the ocean and land during the end-of-life phase of these plastic products.

A.2.3
Loss at End-of-life

Of the total 4'151 kt of additives produced and utilised in packaging materials (830 kt of which used in PET bottles 830 kt), the estimate leakage at end-of-life is ~116 kt to the ocean and 1'122 kt to land (for PET bottles 13 kt and 195 kt respectively), as a large portion of the packaging plastic items is mismanaged.

3.2.4
Final Leakage

In this case study, the final leakage corresponds to the one observed at the end of the product's life, as previously discussed.



B.
Case study, Textiles

B.1 Introduction - Why Examine Textiles?

Textiles not only contribute microfibers to environmental pollution but also pose significant challenges at the macro level for those countries struggling to manage textile waste. The need for sustainable and responsible textile production, consumption, and waste management practices continues to be highlighted.

Microfibers of anthropogenic origin can be classified based on their material source and production methods as synthetic or natural and they have become a widespread environmental pollutant. Both types of fibres (natural like cotton or wool or synthetic) frequently incorporate chemical additives, including colourants like dyes and pigments, as well as finishes such as flame retardants, antimicrobial agents, and ultraviolet light stabilisers. These additives are applied during textile production to impregnate the fabrics with desired attributes such as increased durability. As a result, synthetic fibres are capable of having a long life. They are often transported long distances and accumulate in the environment, where they are ingested by various organisms leading to toxic effects.

For instance, a recent meta-analysis has highlighted the presence of textile microfibres (both natural and synthetic) in terrestrial, freshwater, and marine environmental compartments, even in the most remote of marine ecosystems ecosystems[30] [31] [32]. As a result, organisms even at remote sea depths have been found to accumulate microfibres[33]. Microfibers and their additives therefore become integrated into marine food webs. They are consumed by primary producers and accumulate in higher trophic levels. Constituent pollutants like monomers and plastic additives have the potential to induce carcinogenic effects and disrupt endocrine systems, but plastics can also amass hydrophobic persistent organic pollutants (POPs). Both sources of contamination represent potential exposure routes for marine organisms, with the potential for bioaccumulation and biomagnification through the food chain[34] [35].

Microfibers can also physically obstruct the digestive tracts of animals, reducing their ability to feed, and accumulate on the surfaces of algal cells, diminishing their productivity. These microfibers also obstruct the digestive tracts and tubules of various marine organisms[35]. To compound the issue, chemical additives adhere to the surface of plankton, leading to secondary effects like bioaccumulation in higher trophic levels. For example, the presence of Mono-(2-ethylhexyl) phthalate (MEHP) in the blubber of Mediterranean fin whales (B. physalus) has recently been suggested as an indicator of microplastic ingestion, whether from the water column or through a planktonic vector[36].

Finally, textile additives have toxic effects in humans too. For instance, some consumers may develop dermatitis from prolonged skin contact with antimicrobial finishes. Worse effects are even possible, flame-retardant finishes, DecaBDE for example, belongs to the category of the polybrominated diphenyl ethers (PBDEs) with the potential to disrupt thyroid hormone balance and contribute to a variety of developmental deficits[37].

Textiles constitute a significant source of environmental pollution, and this impact extends beyond the shedding of microfibers during use. When viewed from a macro perspective, the end-of-life of textiles presents a considerable issue across the globe. Excessive textile production and consumption, exacerbated by the fast-fashion industry, result in the generation of significant textile waste. This issue is especially prominent in the Global North, where coping with the accumulation of this challenging-to-recycle material often involves exporting substantial quantities to the Global South. The importing countries often face the challenge of managing the influx of large quantities of textile waste.

Some of these countries in fact may lack the necessary resources, technology, and regulations to handle such a substantial import of textile waste. The consequences of this burden are far-reaching. Improper disposal or inadequate management of textile waste can result in numerous environmental problems, such as soil and water contamination, as well as increased landfill usage. Moreover, it can strain the economic and environmental resources, hindering sustainable development efforts.

In this report the intention is to focus the estimate on the order of magnitude of the microfiber leakage during the use phase, analyse the end-of-life pathways of synthetic textile (particularly clothes) and with both these information sources, estimating the amount of additives that might leak into the ocean as a result of waste mismanagement.

B.2 Results

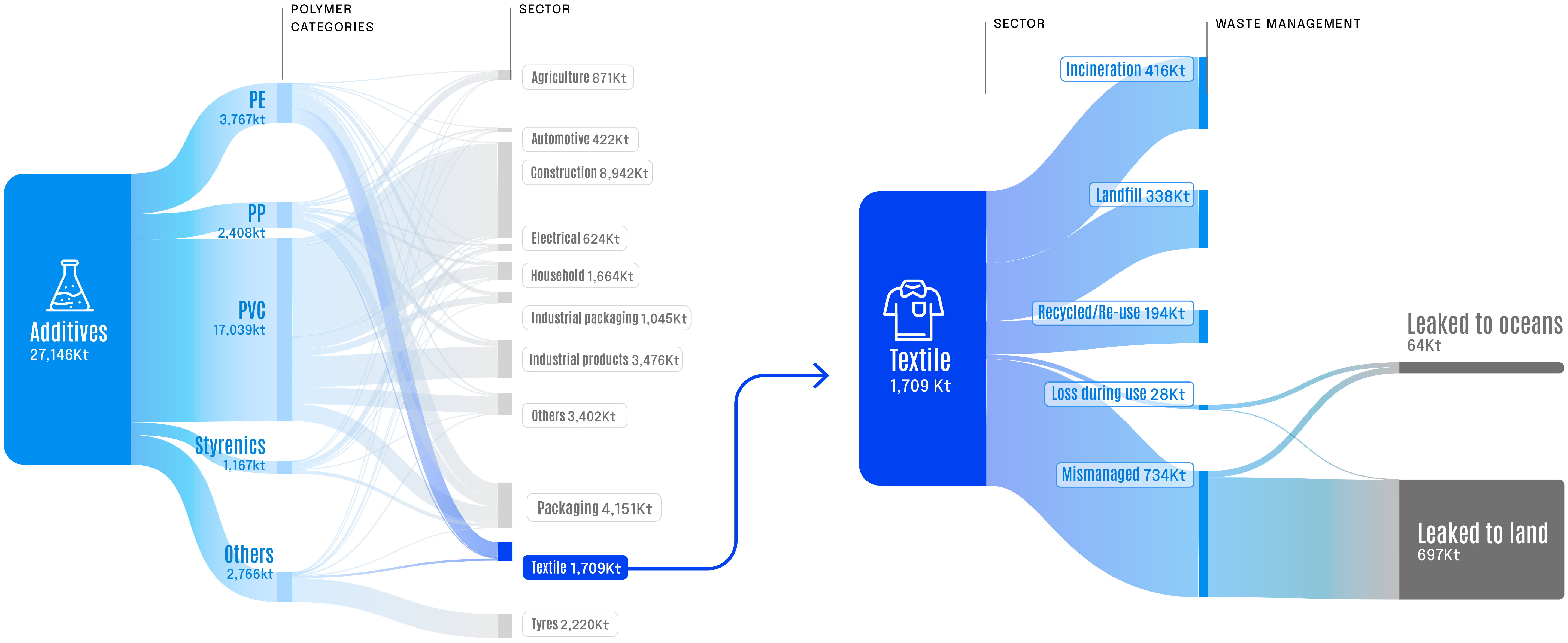


Fig. 10. The Sankey diagram shows the total yearly production of additives that the study estimates used for textiles and the quantities that follow the use and the fate of the garments and can eventually be dispersed in the ocean.

B.2.1 Amount of Additives

The production of clothing has surged over the years, reaching an estimated volume of 53 Mt in 2015, and this growth trend is expected to continue. Fast fashion, with its short-lived garments, exacerbates the issue further. A significant proportion, reaching as high as 97% of textile manufacturing, utilises virgin feedstock and during the manufacturing process a notable quantity, potentially as much as 12% (and in certain regions, even as much as 40%), of the material becomes waste[38]. Regrettably, the global recycling of textile waste remains limited, with only a tiny fraction being integrated into closed-loop systems. A significant portion ends up in landfills or is incinerated, including in illegal dumpsites and through open-burning practices.

The rapid growth of the apparel industry, particularly the consumption of synthetic fibres, has been evident over the past two decades. Currently, synthetic fibres constitute around 62% of all fibres produced, with polyester (52%), polyamide (5%), polypropylene (2.7%), acrylic (1.5%), and elastane (1%) being the primary components[39].

The quantities of additives for synthetic textiles were estimated combining information about the synthetic textile production (around 33 Mt, EMF report) and the average concentration of additives in textile (5.2%)[40], leading to a total of 1'709 kt.

The leakage of textile in the environment happens at three stages: production, use and end-of-life. Nevertheless, for the purpose of this report, only use phase and end-of-life are taken into consider-ation given the scope of the study (see section 3.2 - Page 44).

B.2.2 Loss During Use

Throughout the lifecycle of textiles, from industrial production to household washing, microplastics and microfibers are created due to the abrasion and shedding of fibres. These tiny particles are then discharged into sewage water, ultimately finding their way into the ocean or getting trapped in sewage sludge, which can eventually contaminate the soil.

Numerous studies have investigated the impact of wash temperature on microfiber release, with varying outcomes. While some found no significant effect[41] [42] [43] others noted increased release at higher temperatures[44] [45] [46] [47] [48], potentially due to diverse textile materials used for testing. Interestingly, washing duration does not seem to influence microfiber release significantly, as some studies reported similar releases in short and long cycles[41] [42] [43], with most releases occurring within the first 15 minutes of a wash[43]. However, the washing machine load emerges as a crucial factor influencing microfiber loss, especially when considering specific materials in individual washing processes. Additionally, the number of washes affects microfiber loss, with initial washes releasing more fibres, possibly due to broken microfibers from production processes.

Despite reviewing over 40 research papers, establishing clear correlations between various washing parameters and microfiber loss rates remains challenging, given the diverse conditions studied. Research on natural fibres is limited, leaving this area relatively unexplored. However, friction and agitation within washing machines significantly impact microfiber loss, with factors like load, rotational speed, and agitation levels playing a role. Moreover, studies suggest that microfiber loss rates during production may represent a significant portion of total microfiber loss over a textile's lifetime, potentially accounting for 10-15% of textile mass lost in microfibers[49].

Nevertheless, from literature research it appears that up to 522 kt of synthetic microfibers are lost during the use phase of textile items[17], therefore, with them the study estimates that 27 kt of additives can then be dispersed into the ocean and around 1 kt to land.

B.2.3 Loss at End-of-life

Once textiles reach the end of their life cycle, various disposal methods are employed, including incineration, reuse/recycling, sanitary landfill, or, regrettably, mismanagement leading to their accumulation in dumpsites or littered areas.

The used clothing trade operates through a complex supply chain involving charities, commercial waste collectors, sorters, exporters, importers, wholesalers, and market traders. In this process, used clothes are initially collected by charities and commercial waste collectors in the Global North, they are then sorted and exported to the Global South. However, an unintended consequence of this trade is that many receiving countries in the Global South lack the necessary waste infrastructure to properly manage or dispose of this influx of textiles. The mismanagement of these textiles' items, particularly when they contain chemical additives or pollutants, contributes to environmental degradation and poses health risks to local populations.

From the results of the study, it emerges that, due to mismanagement practices around the world, up to 14 Mt of synthetic textile end up in the environment, representing over 40% of the total synthetic garments produced and consequently 37 kt of additives can then be dispersed into the ocean and 696 kt to land.

B.2.4 Final Leakage

Results of the analysis for the textile end-of-life show that, at a global level, almost half of textile waste is mismanaged, and the fraction of additives that is leaked due to mismanagement practices, cumulated with the loss during use (additives included in the microfibers shredded during washing) adds up to a total of 64 kt of additives reaching the ocean and 697 kt the land.

NOTE TO THE READER:

It is important to acknowledge that additives are not exclusive to synthetic polymers but are also widely used in the production of natural fibres. There is currently no conclusive evidence establishing a clear environmental or health superiority of natural fibres over synthetic counterparts. Consequently, our report does not endorse a blanket preference for natural materials over plastics, or vice versa. The environmental and health impacts of both materials are contingent upon several factors, including the specific additives employed, the utilisation phase, and the effectiveness of waste management practices. Therefore, it is imperative to consider the full lifecycle of materials and assess their impacts holistically, taking into account the substances added, how they are used, and how they are managed at the end of their life.

In addition, the practice of exporting textiles greatly influences the leakage generation. The bar chart below shows the percentage of textile waste mismanaged (that ends up in unsanitary landfills, dumpsites, open burning or is uncollected) by region. The orange bars correspond to the scenario where it was assumed that exported waste is well managed. The blue bars correspond to the percentages which include the actual fate of the export and integrate the mismanaged exported waste.
As an example, EU countries with high GDP present 0% of mismanaged textile waste if we consider the exported waste being managed properly, whereas when considering the actual fate of the exported waste the mismanaged share goes up to 10.5%.

How much textile waste is mismanaged around the world?

When fate of export is **not considered**

When fate of export is **considered**

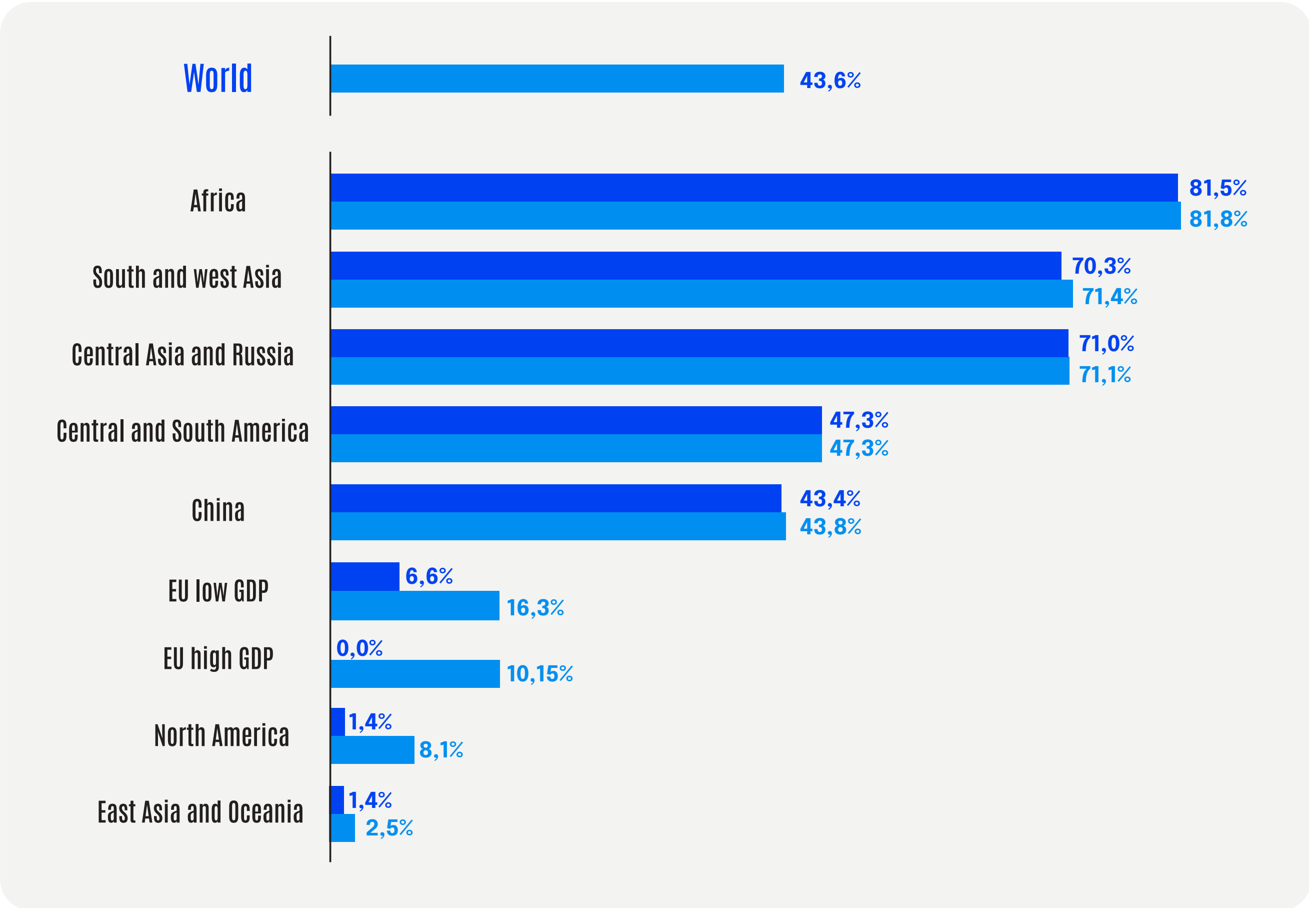
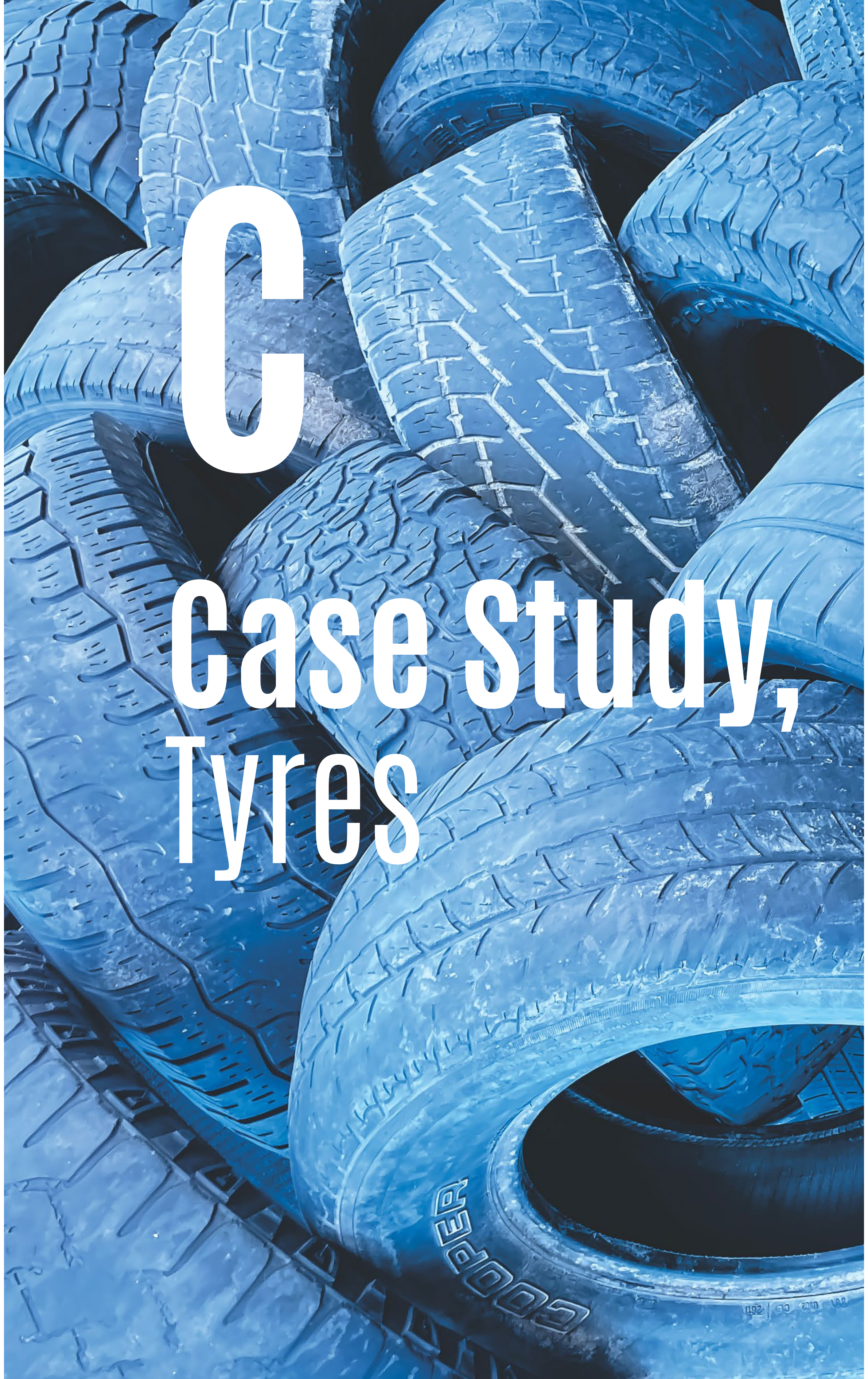


Fig. 11. Percentage of textile waste mismanaged (that ends up in unsanitary landfills, dumpsites, open burning or is uncollected) by region.



C

Case Study, Tyres

C.1 Introduction - Why Examine Tyres?

Since rubber tyres were introduced for all kinds of vehicles, tyre abrasion has been an inevitable process occurring throughout the tyre's lifecycle.

As tyres traverse roadways, a dynamic interaction leads to the creation of particles known as Tyre and Road Wear Particles (TRWPs), primarily composed of a composite of tyre and road materials. However, the life of a tyre doesn't end when it's mounted on a vehicle. There's another crucial phase: the end-of-life journey. Tyres eventually wear out, becoming unsuitable for safe use on the road due to diminished tread depth and structural integrity. During this late phase, tyres often undergo degradation, which not only contributes to the release of more particles but can also lead to the leaching of additives and compounds that were incorporated into the tyre's composition.

The issue of plastic pollution stemming from tyre road wear particles (TRWPs), is increasingly recognized as a significant concern in urban environments. Among all the sources of microplastics in Europe, in fact, automotive tyres are one of the biggest contributors with more than 500 000 tonnes generated per year[18].

For example, the presence of TRWPs in agricultural soils presents a multifaceted challenge with various entry points, including atmospheric deposition and runoff from road surfaces. Another significant aspect is the substantial retention of TRWPs in wastewater treatment plants, where high percentages of these particles are retained. This suggests that wastewater treatment sludge becomes a noteworthy source of TRWPs when utilised as a fertiliser[50]. Consequently, this introduces a complex mix of organic compounds into farmland soils, the ecological consequences of which remain largely unexplored.

Beyond rubber and fillers, tyres incorporate additives crucial to their functionality, including vulcanization accelerators, activators, plasticizers, processing aids, and antioxidants[19]. Vulcanization accelerators like 1,3-diphenylguanidine (DPG) and benzothiazole (BTZ) have been identified in rivers at concentrations measured in micrograms per litre (µg/L). Similar concentration levels have been observed for hexamethoxymethylmelamine (HMMM), a cross-linking agent with an extensive array of transformation products. TRWPs have been implicated as a source of these compounds in rivers[51]. Notably, it's not just the original compounds but also their transformation products, many of which remain unidentified, that might exert harmful effects on ecosystems. For instance, the transformation of the antiozonant N-phenyl-N′-(1,3-dimethylbutyl)-p-phenylenediamine (6PPD) into the significantly more toxic quinone transformation product (6PPD-q) has been linked to coho salmon mortality[52] during their migration to urban creeks to reproduce, generating global interest in studying its occurrence and toxicity in the environment.

One recent study investigated the presence of 15 common tyre additive chemicals in soil, including the emergence of 6PPD-quinone. These findings revealed the widespread presence of these additives, with concentrations ranging from 2.9 to 1440 ng/L. Moreover, TRWPs were detected at 18 out of 21 sampled sites, with concentrations spanning from levels below the method detection limit to values between 690 and 1990 µg/L[53].

Depending on the pathway of TRWPs into fields, certain compounds may leach out even before reaching the soil. Airborne TRWPs may release compounds through volatilization in the atmosphere, but most of these compounds may be expected to be released upon their entry into agricultural soils and interaction with soil pore water. On the other hand, TRWPs deposited on roads undergo exposure to sunlight and rain before entering the sewer system and wastewater treatment plants. In this scenario, TRWPs may have already discharged substantial amounts of compounds due to prolonged contact with the aqueous environment. However, these compounds may still find their way into agricultural soils if wastewater, which is known to carry substantial quantities of TRWP-derived compounds[51], is utilised for irrigation.

C.2 Results

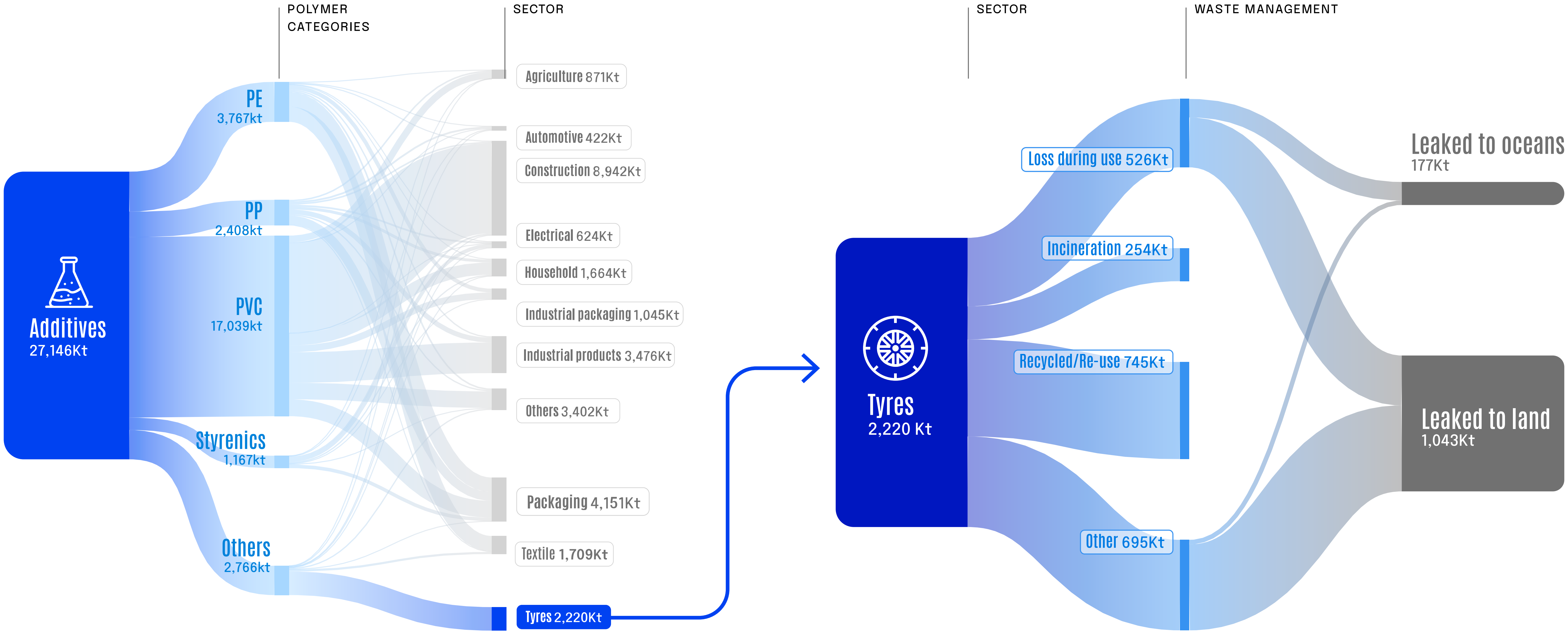


Fig. 12. The Sankey diagram shows the total yearly production of additives that the study estimates are used for tyres and the quantities that follow the use and the fate of these items and can eventually be dispersed in the ocean and land.

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C.2.1 Amount of Additives

Starting with the total weight of the product obtained by combining the production and the tyre weight per unit, and then applying the percentages of additive concentration (please see appendix for more details), the total quantity of additives in tyres was estimated to be around 2220 kt. Since the focus of this report is the plastic constituents, we computed the quantities of additives in tyres based on the material composition of the object itself. This involved considering the percentages of natural rubber, carbon black, and steel in both car and truck tyres. Consequently, of the total 2220 kt of additives in tyres, it is estimated that 589 kt are part of the plastic components of the tyres.

C.2.2 Loss During Use Phase

Friction at the interface between the road pavement and the tyre tread provokes the abrasion of the latter. When tyres are rolling, temperature increases and the elastic and deformable rubber becomes sticky; thus minerals, road and other traffic-related particles may attach to it. With further wear and abrasion, Tyre and Road Wear Particles (TRWPs) - a hetero-aggregate composed of particles from the tread and particles and dust from the road - are emitted to the environment. When abrasion of the tread mainly generates particles of coarse size (10 to 500 μm), volatilization of fine particulates (mainly PM10 and PM2.5) is also possible on local hotspots on the tyre.

From the estimates of this report the content of additives that are included in these particles reaches up to 142 kt every year in the ocean and 384 kt on land.

C.2.3 Loss at End-of-life

Tyres naturally experience wear and tear over time, leading to reduced tread depth and structural integrity, rendering them unsafe for continued use on the road. As they reach the end of their lifespan, tyres go through a degradation process, a phase often characterised by the deterioration of their materials.

This degradation not only results in the release of more particles, but also may facilitate the leaching of various additives and compounds that were originally incorporated into the tyre's composition. This end-of-life trajectory represents a distinct and frequently underestimated source of environmental impact. It is noteworthy for its dual contribution to environmental harm, releasing both particulate matter and chemical additives into the surrounding ecosystem.

From the estimates it appears that the contribution to leakage of additives derived from tyres at the end-of-life is 35 kt every year to the ocean and 659 kt to land.

A word of caution is warranted in interpreting these findings. It is plausible that the presented values might be overestimated, primarily because the authors encountered challenges in sourcing precise data regarding the final destination of tyres as they reach the end of their life cycle–whether they are disposed of in sanitary landfills or end up in unregulated dumpsites–on a global scale. This data gap emphasises the need for more comprehensive and region-specific data to gain a more precise understanding of the environmental impact associated with tyre disposal practices.

Addressing this data limitation is crucial for developing effective strategies to mitigate the environmental consequences of tyre waste.

C.2.4 Final Leakage

Following recent research and the concerns regarding tyres particles leakage in the environment, this study is intended, in part, to underscore the urgency of addressing TRWP contamination, and estimating the leakage of additives in tyres related to the loss of microparticles during use and from the whole tyre at the end-of-life.

Results show that tyres contribute to the leakage of additives into the ocean by 177 kt, the majority of which - 142 kt - comes from loss during usage only and leakage on land is estimated at a staggering 1'043 kt overall.

3.4 Review of the Health and Environmental Impacts Associated with Plastic Additives

The presence of chemical compounds within plastics poses significant hazards to both human well-being and the environment, giving rise to various reasons for concern. This issue carries substantial societal costs, encompassing diseases, cognitive impairments, and even fatalities, all of which translate into diminished economic productivity and increased carbon dioxide (CO_2) emissions.

Minderoo's 2023 report the staggering financial toll of disease, disability and death in the US alone associated with three plastic-associated chemicals (PBDE, PBA and DEHP), with losses estimated at over US $920 billion in just one year (2015).

The following sections explore the adverse effects that plastic additives may cause, acknowledging the intricate nature of this subject. It is recognized that a comprehensive examination extends beyond the scope of this work. However, the objective of this report is to underscore the gravity of this issue, particularly when combined with data concerning the annual release of additives into the environment due to inadequate plastic management practices as provided by this study.

For more comprehensive information, please refer to[1] [20].

3.4.1 Human Health Impacts

The next paragraphs showcase some of the direct and indirect health risks for humans from plastic additives, and how they can pose acute, immediate or chronic health risks to individuals, immediately, or with a latency period.

Ingestion:

Many plastic additives can leach into food and beverages when in contact with plastic containers and packaging. For example, phthalates and BPA are known to migrate from plastics into food. Ingesting these chemicals through food may have adverse effects on health, including endocrine disruption, reproductive issues, and developmental problems, particularly in vulnerable populations like infants and children.

Depending on the conditions in which they are used or stored, chemicals present in plastic products have the potential to migrate to the surface and come in contact with the user. For example, studies have investigated the migration of various substances from plastic containers to food during heating (microwave or conventional heating) and found that some classes of compounds, such as plasticizers, do indeed migrate[9]. Other examples of toxic materials studied for potential release in plastic products include brominated flame retardants (BFRs) (54), SCCPs/MCCPs[55], phthalates[56], bisphenol-A[57], bisphenol-A dimethacrylate, lead, tin, cadmium formaldehyde, acetaldehyde, 4-nonylphenol, methyl tert-butyl ether (MTBE), benzene, and many others. Even in cases where these substances are regulated and some legal thresholds are set for their released concentrations (in food or other products), it was found that there are occasions when the concentrations are considerably higher than the prescribed threshold. Other studies also highlight that the guideline values do not take into account the low levels at which endocrine-disrupting chemicals may come into effect, nor do they consider the toxicity of chemical mixtures which can display combined adverse effects[9].

Dermal Contact:

Some additives can leach out of plastics when in contact with the skin, potentially leading to skin irritations or allergies, especially in cases where individuals have heightened sensitivities to specific additives.

Textiles can include metal nanoparticles, such as silver for antimicrobial purposes or titanium for UV absorption, which can potentially leach from the material and pose risks for both workers and consumers[58]. Numerous investigations have shown that textiles treated with silver particles have the ability to release silver primarily in its ionic form when they come into contact with bodily fluids like sweat, saliva, and urine. The release of silver when these products come in contact with the skin is significant because it can lead to skin discoloration and the potential movement of silver to other organs, such as the kidneys, resulting in temporary increases in the amount of silver in the body[59].

Another example is that phthalate levels exceeding the established EU limits, surpassing 0.1% in mass, have been identified in various products such as nylon sheets, cot mattresses, and diaper changing mats[60]. Other important studies have revealed the importance of dermal exposure[61]: the absorption by skin was comparable with the intake via inhalation in naked participants exposed to gas-phase di (n-butyl) phthalate (DnBP) and diethyl phthalate (DEP) for 6 hours. Furthermore, bisphenols BPA and BPS, have been detected in textiles, including those designed for infants, with concentrations again exceeding the recommended tolerable daily intake proposed by the European Food Safety Authority[62]. Phthalates are also prevalent in textiles featuring polyvinyl chloride (PVC) prints commonly used in children's clothing, with reported concentrations up to 20% of the sample weight[63].

Occupational Exposure:

Workers in industries involved in the production and handling of plastics may face direct exposure to harmful additives. This exposure can lead to occupational health issues, such as respiratory problems, skin conditions, and chemical sensitivities, depending on the specific additives used and the level of protection in place.

There are several production processes to create plastic and plastic products, and one that is particularly noted for occupational hazards is ethylene and propylene production, which is done through catalytic cracking of coal, oil and gas. The workers who are involved in this line of production are exposed to toxic and carcinogenic petrochemicals and additional solvents including benzene, toluene and xylene, 1,2-butadiene, styrene and others[64], which have been proven to be associated with a range of cancers including brain cancer, soft tissue cancer[65], and leukaemia[66] [67] [68]. Increased breast cancer risks are also reported for both men and women employed in plastic manufacturing[69].

Plastic fumes also enter the body through inhalation during moulding, extrusion, and similar processes. The vapour can cause irritation to the nose and throat. Neurological effects include difficulty in concentrating, drowsiness, headache, and nausea. The vapour splashes can also irritate the skin and eyes. At high level exposure, loss of consciousness and death may occur. Long term exposure may affect brain function, including colour and memory function.

One well-known example of health consequences from occupational exposure is vinyl chloride disease. Short-term exposure to vinyl chloride results in headache, nose and throat irritation, shortness of breath, dizziness, coughing, and eye irritation. Chronic exposure to vinyl chloride is associated with an increased risk of developing other diseases, including cancer[70].

Healthcare Materials:

Medical devices and equipment made from plastics may contain additives. Direct contact with these materials during medical procedures or through prolonged use can result in health concerns.

To provide some examples, one of the classes of compounds widely used for example in medications to control drug delivery are phthalates. Phthalates represent up to 40% of medical use plastics by weight[71] and together with BPA and PFAs are found in a wide range of medical devices, presenting a notable source of chemical exposure risk for patients[72].

Lipophilic solutions such as parenteral nutrition, are able to release more lipophilic compounds such as phthalates (DEHP) and adipates (DEHA) from the medical devices[73].

Both phthalates and BPA have been detected in NICU patients, and phthalates are associated with increased risk for cholestasis, necrotizing enterocolitis, and bronchopulmonary dysplasia in newborns[74][75].

Recycling:

Improper disposal practices, such as burning plastics containing additives, can release toxic chemicals into the air, posing a direct health risk to individuals living nearby. Additionally, workers in recycling facilities may be exposed to harmful additives when handling plastics for recycling.

As previously indicated, plastic additives present a significant challenge to improving waste management solutions, and current approaches for managing plastic waste already create hazards and challenges. Research has demonstrated that the majority of existing infrastructures designed for handling discarded plastics can release toxic substances contaminating the air, water, soil, organisms, and impacting public health[76].

For instance, additives pose challenges during the recycling process as they are difficult to remove and tend to accumulate in plastics. These additives, commonly referred to as legacy additives, result in recycled plastic products that are often more detrimental to the environment and public health compared to those made from virgin plastic. This is especially evident in the case of comparing virgin PET with recycled PET (rPET), where higher migration of substances such as Antimony and Bisphenol A has been reported[24].

This is attributed to multiple contamination sources and the variability in collection and sorting practices, and the efficiency of decontamination efforts.

Each recycling method, being it mechanical or chemical, subjects plastics to further transformation from melting to the extrusion process or pyrolysis. Each of those processes can emit chemicals into the workplace air including VOCs and PHAs. The issue becomes even more concerning for these workers as melting recycled plastic pellets releases toxic chemicals in considerably higher quantities than virgin plastics[77].

On another note, although chemical recycling accounts for less than 0.5% of recycled plastic waste, it is still influenced by the presence of additives. While certain chemicals in plastics are largely destroyed in some of these processes, others may persist (such as heavy metals) or generate problematic degradation products, which pose environmental and health concerns, as well as technical challenges. For example, the pyrolysis of plastic waste containing halogenated flame retardants can produce highly toxic halogenated dioxins and furans, along with acidic gases and while recycling plants should be well-regulated with controlled working conditions, some facilities are still not properly equipped or monitored[22][78].

While plastic recycling is often effective in giving new life to old materials, the risks from the additives in the plastic remain. It has been demonstrated that hazardous chemicals leach in larger quantities from recycled plastics than from virgin plastic, the recycling processes may, in fact, concentrate or introduce new chemicals to the material value chain[79].

The presence of mixtures and unknown chemicals further complicates recovery processes and can trigger unintended chemical reactions. Furthermore, the process of recycling post-consumer plastics causes their degradation, requiring the use of additional additives such as stabilisers, compatibilizers, and reactive additives. These additives are crucial to achieve the desired properties that enable recycled plastics to compete with more resistant virgin materials but, in turn, present additional risks.

Inhalation of Fumes
(Incineration and Open Burning):

When plastics containing certain additives are heated or burned, they can release toxic fumes and particles into the air. Inhaling these fumes can result in respiratory problems and other health issues.

Uncontrolled and unregulated burning of plastic waste, especially plastics that contain halogen-based compounds like PVC, polytetrafluoroethylene (Teflon), or brominated flame retardants, can lead to the release of harmful substances. This includes unintended pollutants like persistent organic pollutants (POPs), such as dioxins[80]. Humans with short-term exposure to high levels of dioxins may experience skin lesions, such as chloracne and patchy darkening of the skin, as well as altered liver function. Long-term exposure is linked to impairment of the immune system, the developing nervous system, the endocrine system, and reproductive functions[81].

3.4.2 Environmental Impacts

The following paragraphs address how chemicals in plastic can affect both water and soil, and disrupt the ecosystem and food chain.

Water Contamination:

Chemical additives from plastic can leach into water bodies, such as rivers, lakes, and oceans, contaminating aquatic environments. This contamination can disrupt aquatic ecosystems, impacting the health of aquatic life, potentially entering the food chain and eventually contaminating humans through seafood consumption.

The leaching of additives from plastic particles into marine waters is a pressing concern due to the efficient absorption of hydrophobic organic chemicals (HOCs).

This phenomenon has sparked hypotheses regarding the role of microplastics in transporting HOCs and their potential contribution to the bioaccumulation of HOCs in marine organisms[82][83]. Polymers have long been recognized as a source of HOCs for organisms, forming the basis of passive dosing approaches in ecotoxicology[84][85].

Recent research, as reported by Suhrhoff and Scholz-Böttcher (2016), reveals that turbulence significantly amplifies the leaching of additives from plastic particles into the aquatic environment. While Bisphenol A (BPA) exhibited a modest 11% increase in leaching from PVC under turbulent conditions due to its higher water solubility, other PVC additives displayed more pronounced effects, with leaching increasing by 20 to 79 times. Phthalates, less soluble in water, experienced enhanced solubility in turbulent conditions. The most substantial impact was observed with Irgafos® 168 phosphate leaching from polyethylene (PE), increasing 190-fold compared to ambient seawater conditions, resulting in the release of nearly 10% of the initial content. This heightened leaching poses long-term implications for polymer stability, including increased chemical oxidation and fragmentation into microplastics, potentially exacerbated by UV radiation exposure. While some additives, such as phthalates, mellitates, styrene oligomers, and Irgafos® 168 phosphate, were leached well below 0.1% of their initial concentrations, others like ATBC and its derivatives and BPA exhibited more substantial leaching, exceeding 10% and 3.8%, respectively[86].

Soil Pollution:

When plastic products are used in agriculture or improperly disposed of in landfills or as litter, the chemicals they contain can leach into the soil. This can lead to soil pollution, affecting soil quality and potentially harming plants, animals, and even humans through contaminated agricultural produce.

The extensive use of plastic film, particularly polyethylene (PE) mulches, in agriculture has become commonplace, offering valuable benefits such as temperature control, moisture retention, and weed suppression, ultimately enhancing crop yields. However, the residues of conventional plastic mulch can persist in agricultural soil for extended periods, giving rise to long-term environmental concerns. Even the smallest fragments of plastic mulch that integrate into the soil or undergo repeated fragmentation can release a diverse array of additives, including plasticizers, stabilisers, and chain extenders, into the agricultural landscape.

The utilisation of plastics in agriculture presents a pathway through which plastic fragment residues and additives are introduced into the soil. These materials, once within the soil matrix, have the potential to spread to adjacent environments via precipitation and irrigation. Numerous studies have documented the presence of plastic additives in agricultural soil, encompassing plasticizers, antioxidants, and stabilisers[87][88][89][90].

As an example, the introduction of Bisphenol A (BPA) into the soil environment occurs through multiple pathways, including sludge and effluent discharge. In Korea, BPA has been detected at levels ranging from 0.5 to 48.68 mg/kg within the soil environment, as reported by the National Institute of Environmental Research in 2006[91]. Soil concentrations of BPA were measured at 2340 pg/m3 in China, 1920 pg/m3 in Japan, and notably, 17,400 pg/m3 in India. In the United States, the U.S. The Environmental Protection Agency recorded varying BPA concentrations in 2010 with levels ranging from 4 to 14 mg/kg in soil[92]. Also in the United States, Kinney et.al. reported finding 32 to 147 mg/kg of BPA in agricultural field soil in 2008[93]. Additionally, at a golf course in California, Xu et al. (2008)[94] measured BPA concentrations ranging from 0.55 to 2 mg/kg. Research by Gibson et al. in 2010[95], revealed BPA concentrations in Mexican agricultural field soil irrigated with wastewater, spanning from 1.6 to 30.2 mg/kg. Staples et al. (2010)[96] reported median BPA concentrations of 0.24 mg/kg in European soils that had been amended with biosolids, with the 95th percentile concentration of BPA reaching 140 mg/kg.

Plastic degradation within landfills initiates the release of breakdown products, a process that varies among different plastic types and generates distinct degradation by-products. This includes the production of aldehydes and ketones from polyethylene (PE), hydrochloric acid from polyvinyl chloride (PVC), pentanes from polypropylene (PP), as well as oligomers of styrene, ethyl benzene, phenol, and benzoic acid from polystyrene (PS). Furthermore, polyethylene terephthalate (PET) contributes acetaldehyde, ethylene, benzene, and biphenyl to the mix, typically at concentrations within the range of 0.1 to 7 mg/L. These pollutants have the potential to escape into the surrounding environment, whether through the air or water pathways[97]. In addition to these breakdown products, landfill leachate can carry a host of contaminants, including metal(oid)s, plastic additives, and the constitutional monomers present in plastic waste. A case in point is the presence of Bisphenol A (BPA) in leachates from municipal waste disposal sites in tropical Asia, where BPA concentrations reach several mg/L. As a result, landfill leachate is recognized as heavily polluted water, necessitating specialised treatment approaches encompassing physical, biological, and chemical methods[98]. The interaction of rainfall with landfill sites, particularly those lacking impermeable bottom liners or protective top cover layers, results in the dissolution of both organic and inorganic pollutants into leachates. These leachates can subsequently infiltrate the soil, leading to contamination of underground water systems, or they can enter surface waters, such as rivers, via runoff. Notably, elevated levels of polybrominated diphenyl ethers (PBDEs), for instance, have been observed in groundwater near open dumpsites, underscoring the far-reaching implications of plastic waste within landfill environments[99].

3.5 Conclusions

Every year approximately 27 Mt of plastic additives become waste along with the plastic products they are found in. This study finds that up to 971 kt of additives used in plastic find their way into marine ecosystems annually, with 5'650 kt leaking into terrestrial environments.

In particular, approximately 116 kt of additives are discharged into the ocean from disposed packaging, 64 kt from synthetic textiles during use and at the disposal phase, and 177 kt reach the oceans from tyres, the majority of which - 142 kt - comes from loss during the usage phase.

This leakage occurs through various pathways, and is often due to the absence of an adequate waste collection system or littering, and/or improper plastic product disposal. Once in the marine environment, these additives can have detrimental effects on aquatic life, ecosystem health, and human well-being.

This study's authors project that without significant changes in plastic production rates, chemical composition, or improvements in waste management practices, the annual leakage of plastic additives into oceans and waterways would be expected to increase by over 50% annually by 2040.

The findings of this report therefore emphasise the need for a comprehensive and informed approach towards managing plastic additives when addressing the broader plastic pollution issue.

The widespread use of additives in plastic, coupled with the significant waste production and consequent leakage of these additives into oceans and waterways, highlights the urgent need for action by scientists, policymakers, and manufacturers.

Several key recommendations emerge from this study:

First, **polymer selection** plays a vital role in minimising waste at the end of use. Choosing polymers that are easily reusable or recyclable can significantly reduce the amount of plastic waste generated. By carefully selecting the appropriate polymers, a more sustainable and circular model for plastics can be promoted.

Simplifying designs and limiting the different polymers as much as possible is another important aspect. Complex product designs with multiple polymers make recycling and sorting more challenging and less efficient. Simplifying designs might help facilitate the recycling process and enhance the quality of recycled materials.

Maximising the production of **high-quality recycled materials** is essential. Investing in efficient recycling technologies and processes ensures that the output of the recycling process meets stringent quality standards. This promotes the use of recycled materials in manufacturing, reducing the dependence on virgin plastics.

Specifically for additives, to address this issue effectively it is crucial to prioritise the **reduction or substitution of specific chemical compounds.** Establishing a list of problematic additives, considering both direct and indirect impacts, will enable informed decision-making. This list must be comprehensive and capable of integrating new molecules as they are created. Additionally, further research is required to enhance the understanding of how and when additives (and their degradation products) are released (leached) into the human body and the environment, so that this can be prevented.

Furthermore, **minimising** the amount of **chemical hazards and exposure at the production level and end-of-life** is paramount. Careful chemical selection and evaluation can help reduce the potential environmental and health impacts associated with plastic production and disposal.

The necessity of plastic items in our modern world is well-understood, as they serve critical roles in numerous important applications, from medical devices to infrastructure materials. However, considering the environmental concerns and the detrimental impact of plastic pollution, there is an urgent need to discern between essential and non-essential plastic items. It is imperative that **non-essential plastic products undergo stricter regulations,** not only in terms of polymer usage but also in the careful scrutiny of the chemicals employed in their production.

Plastic pollution is rooted in the imbalance between the volumes of plastic that are produced and used, and the world's ability to manage those volumes when they become waste. **Aligning polymer selection with waste management operations** in the intended market is also crucial. Understanding the local infrastructure and capabilities for waste management allows for better integration of recycling systems and maximises the efficiency of plastic waste processing. Effective waste management plays a pivotal role in mitigating the risks associated with plastic additives. Merely managing plastic waste though does not ensure the appropriate handling of additives. A careful examination of waste management practices is necessary to consider the combined effects of various disposal methods, such as incineration, and their subsequent release of chemicals into the environment. It is essential that waste management of plastics and additives be explored more deeply so that research and science can further a comprehensive understanding of related issues and the creation of appropriate solutions.

Mitigating the risk of littering should be considered as well. Implementing measures such as improved waste management practices, public awareness campaigns, and the development of innovative packaging solutions can help reduce litter and prevent plastic leakage into the environment.

Lastly, ensuring **transparency** of chemical composition is vital. Providing clear and accessible information about the chemical components used in plastic products enables informed decision-making by consumers, regulators, and other stakeholders. Transparency also means integrating the accountability of additives leakage in the environment in plastic leakage modelling and in platforms such as PLASTEAX.

In conclusion, a multi-faceted approach is necessary to tackle the complexities associated with plastic additives. By incorporating these recommendations into the design and management of plastics, we can move towards a more sustainable and environmentally responsible approach to plastic waste, minimising its negative impacts on nature and human health.

Most countries have or are developing laws and standards to regulate the use of chemicals in plastic, but further research and scientific investigation are essential to help regulatory bodies prioritise risk and control measures to enforce regulations.

By adopting such an approach, significant steps towards a more sustainable and environmentally conscious future can be made.

4 Appendix

4.1 Glossary

For the purpose of this report, terms are defined as follows:

Additives in plastic: Chemical compounds added during plastic compounding (the process of mixing or blending polymers and additives in a molten state) to fulfil specific desired functional properties in the production process or in the final plastic product. These chemicals present various kinds of classifications, depending on their chemical structure and/or their function. In this report we focus on 5 main categories: plasticizers, flame retardants, heat stabilisers, fillers, antioxidants as they represent over 86% of the production (a 6th category in this report, named "others" refers to the additives which are not part of those main categories). Over 75% of all additives are plasticizers, fillers and heat stabilisers.

Antioxidants: Antioxidants are essential additives in plastics to safeguard against degradation caused by thermo-mechanical or thermo-oxidative conditions. These compounds extend the product's lifespan, enhance its appearance, and maintain its strength, stiffness, and flexibility. Various types of antioxidants, such as amines, phenolics, phosphites, and thioesters, are utilised in plastics to interrupt the degradation process based on their unique structures.

Fillers: Fillers are incorporated into polymer formulations to improve properties and reduce costs. They can be in the form of solid, liquid, or gas and effectively replace expensive resin without compromising other characteristics. The choice of filler significantly impacts the properties it imparts, which depend on the filler's physical and chemical characteristics. Examples of fillers used in plastics include alumina trihydrate, kaolin clay, calcium carbonate, and talc. Mineral fillers, for instance, can enhance the moldability and stability of plastics and increase heat-resistance for specific applications.

Flame Retardants: Flame retardants are chemical compounds added to plastics with the primary objective of inhibiting or retarding ignition and burning. By designing thermally stable polymers less prone to decompose into combustible gases under heat stress, combustion can be prevented. Flame retardants can be classified into two categories: additive and reactive. Additive flame retardants are physically mixed with the polymer, while reactive flame retardants act through chemical reactions. Both types can influence polymer properties such as viscosity, flexibility, and density.

Heat Stabilisers: Heat stabilisers protect polymer compounds from heat damage during the manufacturing process or in the final product's normal use. Virtually all polymer types benefit from heat stabilisers, with polyvinyl chloride (PVC) being a common example. These additives preserve the polymer's appearance, strength, elasticity, durability, and performance characteristics. Heat stabilisers can be classified into two types: organophosphates, which protect during manufacturing, and phenolic antioxidants, which protect during the product's usable life. The choice of heat stabiliser depends on the polymer's manufacturing, processing, and usage conditions.

Improperly disposed: waste fraction that is disposed in a waste management system where leakage is expected to occur, such as a dumpsite or an unsanitary landfill.

Inclusion rate: the ratio of the additives weight to the total weight of the plastic compound.

Leaching: A chemical substance leaches or is leached from a material when it is removed by the action of a solvent passing through the material. In the context of this report we consider "leaching" the release of additives in food from food content material, to skin from garments.

Leakage: Plastic that is released into the environment. This study aims to differentiate between two types of leakage: leakage into the oceans and waterways, and leakage into land, soil, and other terrestrial compartments. Moreover, in this report, the term "leakage" in the context of additives refers to the quantity of chemicals that are contained in the plastic product that is leaked, and does not investigate the leaching of those chemicals from the plastic material itself.

Macroplastics: Large plastic waste readily visible and with dimensions larger than 5 mm.

Microplastics: Small plastic particulates below 5 mm in size. Two types of microplastics are contaminating the world's oceans: primary and secondary microplastics.

Mismanaged waste: the sum of uncollected and improperly disposed waste.

Non-fibre plastic: any type of plastic material that does not contain or consist of fibres. Fibres are typically elongated, thread-like structures, while non-fibre plastics are solid, homogeneous materials without a fibrous structure.

Non-intentionally added substances (NIAS): chemical compounds found in plastic, which are not intentionally introduced during the manufacturing process, and may arise from the degradation of either or both the polymer and the additives or due to external contamination.

Plastics: solid materials that contain, as an essential ingredient, one or more high-molecular-mass polymers, and which are formed (shaped) by heat and/or pressure during either the manufacture of the polymer or the fabrication into a finished product. This material may be shaped when soft and then hardened to retain the given shape.

Plasticizers: Plasticizers are low-volatility liquid or solid substances added to raw polymers like plastics or rubber to enhance flexibility, ease of shaping and moulding, and reduce surface friction. Once added, plasticizers work into the polymer chains, acting as a buffer between molecular segments. There are different families of plasticizers, including phthalates, dicarbonates, phosphates, and fatty acid esters. These additives allow for the tailoring of properties to meet specific application requirements.

Polymers: natural or synthetic long-chain substances consisting of sequences of one or more types of monomers.

Production: the term refers to polymer production which is either from primary virgin source or secondary source (recycled plastic from previous year). For the purpose of this report, it does not include the manufacturing of final products, as this would lead to double counting for the reported geographies.

Properly disposed: waste fraction that is disposed in a waste management system where no leakage is expected to occur, such as an incineration facility or a sanitary landfill.

Release rate: ratio between mismanaged waste and leakage.

Textile: any fabric or cloth, especially those that have been woven, any raw material suitable to be made into cloth; fibre or yarn. They can be either made out of natural material (cotton, wool, silk…) or synthetic (polyester, nylon…). For this report we refer to textile as those which are made into garments, specifically synthetics.

Tyres: a rubber covering, typically inflated, or surrounding an inflated inner tube, placed round a wheel to form a soft contact with the road. Tyres are generally composed of several materials, some polymers (synthetic and natural rubber) and some non-polymers (additives, steel, carbon black etc..). For this report we consider the additives used in the whole object.

Uncollected: waste fraction that is not collected, either by the formal or the informal sector. It includes littering (the act of dropping rubbish in the environment).

Sources: (100) (101) (102)

4.2 Methodology all Plastics

4.2.1 Use Phase

N/A

4.2.2 End of Life

Literature has reported that up to 31'000 kt of plastic (excluding natural rubber used in tyres) leak to terrestrial compartments plus 49'000 kt that are burned in open air[103] and 12'000 kt to oceans and other waterways[17].

4.2.3 Additives calculations

This section contains the explanation of the methodology used for the calculation of end-of-life of plastic used in all sectors but Packaging, Textile and Tyres.

The leakage was calculated by applying an average percentage of additives in plastic, 7% [5]. This means that out of the 19'066 kt of additives, 3'010 kt leak directly into land or oceans plus 3'434 kt that are potentially released in the environment due to open burning.

4.3 Methodology Pet Bottles

4.3.1 Use Phase

N/A

4.3.2 End of Life

This section contains the explanation of the methodology used for the calculation of end-of-life for PET bottles.

Global Values for PET Bottles End-Of-Life

Data was sourced from the PLASTEAX database, which offers country-specific waste management statistics tailored to specific polymer types and applications. By selecting PET as the polymer and bottle as the application, we accessed data explicitly characterising the end-of-life scenarios for PET bottles. This comprehensive dataset covered over 60 countries, collectively accounting for approximately 80% of global PET bottle production. This dataset was consequently used as a foundational reference to construct global-level figures.

For each country, the authors reviewed data on the waste production and the associated percentages of different fates (recycling, incineration, sanitary landfill, unsanitary landfill, littering, uncollected and exported). The percentages of unsanitary landfill, littering and uncollected all together constitute the mismanaged waste figure. To derive global data, the fate of the exported waste was investigated first, similar to what was done for textiles. Country exports were then reviewed to understand how much of the exported plastic is mismanaged after export, reintegrating this quantity in mismanagement volumes attributed to the exporter. Lacking data on the other fates, the exported portion that is not mismanaged was reallocated to recycling, incineration and sanitary landfill according to global averages. Once these data for all countries were compiled, global percentages were obtained by taking a weighted average based on waste production of the countries.

The release rate for PET bottles, representing the percentage of mismanaged waste that ultimately finds its way into the environment, was pre-modelled within the PLASTEAX framework and remained unaltered in the current analysis. This rate stood at approximately 6.3%, notably lower than the average of 10% suggested in the PLP guidance[104]. This divergence can be attributed to the high intrinsic value of PET bottles within both formal and informal recycling markets, diminishing the likelihood of their ending up in oceans and waterways.

4.3.3 Additives Calculations

To estimate the amount of additives in packaging, and consequently in PET bottles, the total amount of plastic production (non-fibres) was considered first for the year 2021(ICIS 2021 and internal computation EA). The 7% average was then applied to estimate the quantity of additives in plastic. The additives quantity was then redistributed by classes of polymers (PVC, PE, PP, Styrenics, and others) according to Andrade et al. [16]. From here the quantities of plastic by sector and by polymer were used (internal computation at EA thanks to PLASTEAX) [12], to redistribute the additives by sector and to establish the particular amount of additives used in packaging.

Loss during use:

N/A

Loss at end of life:

The quantities for PET bottles were extracted from packaging quantities by starting with a 20% portion (PLASTEAX, internal computation by EA). So this means that out of the 4151 kt of additives used in packaging, 830 kt are used in pet bottles. Because the pet bottles waste generation is estimated at 25 Mt (PLASTEAX scaled up based on region populations), the percentage of additives used in pet bottles is around 3.3%. Out of these 830 kt, we have 13 kt that finally leak into the oceans at the end-of-life (25% is mismanaged and then the release rate is around 6.8%, which gives a leakage rate of 1.56%).

The quantities for packaging were calculated removing the quantities for pet bottles (20%) and then the e-o-l for generic packaging was applied to them. (31% mismanaged and 10% release rate, so 3.1% that leaks). This means that out of the 3321 kt of additives in packaging (excluding pet bottles), 103 kt leak into the oceans at the e-o-l. Together with the 13 kt coming from pet bottles, this gives a total of 116 kt of additives leaking into the ocean from packaging.

4.4 Methodology Textiles

4.4.1 Use phase

From literature 522 kt of microfibres lost during use[17].

4.4.2 Use phase

This section provides a description of the methodology employed for calculating the end-of-life scenarios for synthetic textile waste. It includes global averages encompassing various disposal outcomes, such as recycling, incineration, sanitary landfill, unsanitary landfill, re-use, as well as percentages for uncollected waste and exported waste. The Mismanaged Waste Index (MWI) for textile waste is derived by adding up the percentages of waste that remains uncollected and those that are improperly disposed of, particularly in unsanitary landfills.

Calculation of global values

The process of determining global percentages involved data collection from 23 strategically chosen countries (see below), globally significant in terms of synthetic textile waste production and importation. These countries served as the basis for regional modelling, where global values were synthesised using a weighted average approach based on the waste generation patterns within each region. Of particular significance in the current analysis was the examination of exported waste. While exported waste is commonly assumed to be well-managed,this study incorporated an additional layer to explore the actual fate of exported waste. This investigation was prompted by the well-documented phenomenon of waste exportation, especially from the Global North to the Global South, significantly contributing to global plastic pollution due to the inadequacy of waste management infrastructure in the importing Global South nations. This analysis affirms this perspective, demonstrating a notable increase in the MWI for regions such as Europe or North America as a consequence of this practice.

Modelization of end-of-life at national level

The approach used in this report to establish a textile-specific MWI for individual countries involves a structured three-step methodology.

Data Collection: In the initial step, country-specific data is gathered pertaining to the separate collection of textile waste and its subsequent waste management practices. This data is acquired through a comprehensive literature review process.

PLASTEAX Database: Subsequently, data from the PLASTEAX database is incorporated, which provides valuable insights into the collection rates and end-of-life outcomes of municipal solid waste. This is useful because it is assumed that textile waste which is collected but not separately collected is typically integrated into the broader stream of municipal solid waste and follows its pathways.

Integration and Assessment: The final stage entails the synthesis of these two datasets. Textile waste, when separately collected, follows distinct disposal pathways, whereas the remainder is typically disposed of as part of municipal solid waste. Moreover, an uncollected rate is factored in to account for instances in which a country does not achieve full waste collection coverage.

Regional Considerations and Model Countries: For the purpose of this study, various regions were considered, each represented by a selection of key countries to serve as modelling references. These countries were chosen to reflect the waste generation and management dynamics of their respective regions.

- **Africa:** Kenya, Nigeria, Tanzania, and Tunisia
- **Central and South America:** Brazil
- **Central Asia and Russia:** Russia
- **China**
- **East Asia and Oceania:** Japan
- **North America:** United States of America
- **South and West Asia:** India and Pakistan
- **Europe high GDP:** Denmark, Finland, Germany, France, Netherlands, and Sweden
- **Europe low GDP:** Spain, Estonia, Czechia, Latvia, Lithuania, and Poland

Note: *The authors acknowledge that some of the data for countries might not be fully representative of their region. Nevertheless, the authors believe this classification is the best possible one with the available resources. To have better representation more data will be needed at country-level for all regions (especially for East Asia and Oceania).*

Analysis on exported textile waste

Data on the textile waste trade was utilised, looking at where a country exports its textile waste. For each of the regions the country exports to, textile waste management was modelled, and these percentages were used to redistribute the portion of exported waste by the country of interest. This was done for each region a country exports to, and by summing up the different fates the figure could be put back together in the country's waste management values. Basically, if a country exported 5% of its generated textile waste, after the analysis this 5% will be redistributed to the different fates, and if some of it ends up being mismanaged this is added to the mismanaged textile waste index of the country.

For the release rate, a value of 5% was chosen according to the PLP methodology [104] assuming textile is of large size (>25 cm) and of low value.

Data on the textile waste trade was utilised to conduct an assessment of the destinations to which a country exports its textile waste. For each of the regions that receive these exports, the management of textile waste was modelled, thereby determining the corresponding percentages allocated to different disposal methods. Subsequently, these derived percentages were applied to redistribute the portion of textile waste that the country of interest exports to each region. This process was executed for each region to which the country exports. By aggregating the diverse fates of exported textile waste, this information was integrated into the country's overall waste management analysis.

In essence, if a country, for instance, exported 7% of its generated textile waste, the analysis done for this report effectively reallocated this 7% across the various disposal outcomes. Importantly, any portion of the exported waste that ended up being mismanaged was incorporated into the country's mismanaged textile waste. In establishing the release rate, a value of 5% was adhered to, following the guidelines outlined in the PLP methodology [104]. This choice was based on the assumption that the textile waste in question is of substantial size (>25 cm) and is considered of low economic value.

4.4.3 Additives calculations

The quantities for textiles were built combining information about the textile production (33 Mt, EMF report) and the average concentration of additives in textile (5.2%,[40]).

Loss during use:

From literature 522 kt of microfibres lost during use and an average inclusion rate of additives of 5.2%[40] results in an estimated 27 kt of additive lost during use to ocean and 1 kt to land given by the fate of the sewage sludge which contains the captured microfibres and is put in agricultural soil as fertiliser.

Loss at end of life:

From a total 1682 kt of additives estimated at the end-of-life, using the average global mismanagement rate and applying a release rate of 5% (PLP methodology) we get 37 kt of additives leakage from textile at e-o-l.

4.5 Methodology Tyres

4.5.1 Use phase

Internal computations by EA, based on the Plastic Leak Project model[104] estimates that up to 3'565 kt of microplastic are lost during use.

4.5.2 End-of-life

The data utilised in the current analysis were sourced from the paper authored by Valentini et al. (2022). Within the dataset, a composite category comprising 41% of unspecified uncollected waste, sanitary landfills, and dumpsites was encountered. In the absence of more granular data, this category was treated as a proxy for mismanagement, although it is acknowledged that this approach likely results in an overestimation of the actual mismanaged quantity.

For waste generation statistics, data on the global production of tyres, distinguishing between car and truck tyres, was derived from the research conducted by Sienkiewicz et al. (2012)[(105)].

The distribution between these two categories of tyres, specifically for cars and trucks, was obtained from the same source, as well as the paper authored by Valentini et al. (2022)[(106)].

Regarding the release rate, a value of 5% was adopted following the guidelines outlined in the PLP methodology[(104)]. This assumption was made under the consideration that tyres are generally of substantial size (>25 cm) and are characterised as being of medium value within the waste management context.

4.5.3 Additives calculations

For tyres, the total weight was computed by combining the production and the tyre weight per unit, differentiating between cars and trucks (the weight of a tyre changes greatly). he percentages of additive concentration in truck tyres and in car tyres were then applied[(105)]. This gives a total quantity of additives in tyres of 2220 kt. Of this, 142 kt are lost and leak to the ocean during use (internal computation at EA), therefore 2077 kt are additives present at the e-o-l. Using data from Valentini et al. (2022[(106)], it is assumed that up to 41% of this quantity is mismanaged, and then 5% is released to the oceans, with 43 kt of additives therefore leaking at tyres e-o-l.

A note on tyres methodology: it was necessary to compute the quantity of additives present in the non-plastic components of tyres. To do so, the percentages of natural rubber, carbon black and steel in car tyres and in truck tyres was used. So finally, out of the 2220 kt of additives in tyres, 1630 kt are in non-plastic components and this gives a quantity of 589 kt in tyres plastic components.

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